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Doctor's Dissertation

Investigation of the Environmental Factors Which Affect the Anaerobic Decomposition of Fibrous Sludge Beds on Stream Bottoms

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INVESTIGATION OF THE ENVIRONMENTAL FACTORS WHICH AFFECT THE ANAEROBIC DECOMPOSITION OF FIBROUS SLUDGE BEDS ON STREAM BOTTOMS

A thesis submitted by

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SUMMARY

An environmental problem associated with paper mills is fibrous sludge deposits, caused by fiber loss from the mill to the river. The fiber mixes with particulate materials in the river, and this composite settles to form deposits on the river bottom. Bottom deposits which contain more than 5% by weight fiber are considered to be fibrous sludge beds.

Fibrous sludge redistribution and decomposition in the Lower Fox River between Lake Winnebago and Green Bay, Wisconsin, have been studied. Field surveys of the river were made to determine the sludge distribution and the variation in sludge properties with location in the river. In June, 1970, approximately 50% of the river bottom was covered with fibrous sludge to a depth which ranged from six inches to several feet. A mathematical model developed to predict sludge distribution appeared to depict actual river conditions quite well. Approximately 4/5 of the Lower Fox River is subject to sludge deposition, scour, and redistribution; while the remaining 1/5 is either always free of sludge or contains permanent beds. Sludge beds disappear from a given location in the Lower Fox River by three principal mechanisms: scour, flotation, and decomposition. The principal mechanism for sludge bed destruction is decomposition, since scour and flotation merely relocate the sludge at another position in the river. There are sufficient quantities of nutrients present in the sludge to sustain active decomposition. Sludge beds act as a stagnant body of water through which heat is conducted. A linear temperature profile is found in the bed, indicating that the energy generated by the decomposition process is negligible in comparison to that conducted in from outside the bed.

Laboratory studies were conducted which demonstrated that anaerobic decomposition is the principal mechanism for the destruction of organic matter in a sludge bed. Chemical pulps anaerobically decompose faster than do groundwood

pulps of similar surface-to-volume ratios by a factor of about two. The rate-limiting step in the anaerobic decomposition process is the breakdown of cellulose into glucose and/or cellobiose. Temperature has an appreciable effect on the rate of fibrous sludge anaerobic decomposition. The rate increases linearly with temperature over the range from 10 to 25°C. approximately threefold for each 10°C. Sudden changes in temperature within a 5°C. range do not cause shock inhibition of the decomposition. Fibrous sludge decomposition either ceases or proceeds very slowly below 4°C. The anaerobic decomposition system in the Lower Fox River is not limited by mass transfer.

Sludge bed behavior and conditions vary with time of the year and with river position. Bed properties vary with position in the Lower Fox River but are generally of the same order of magnitude. Appreciable differences in rate of decomposition occur at different river locations and at different times of the year in the same location.

The life of a fibrous sludge bed in the Lower Fox River would be one to two years if no new material were added to the bed. The amount of volatile solids destroyed by anaerobic decomposition in a year is approximately equal to the amount of volatile material which would be added to the river by the mills along its banks if the 1972 Wisconsin Department of Natural Resources water quality standards are met.

INTRODUCTION

A significant environmental problem associated with the paper industry is fibrous sludge deposits, the result of fiber loss from the mill to the stream. The fiber mixes with the natural particulate matter in the river and settles with it to form fibrous sludge beds. These sludge beds are objectionable because of the oxygen demand they exert on the river, the odorous gases they evolve, and the biological deserts (areas void of normal benthal life) they create on the river bottom. Past studies of sludge beds have emphasized their oxygen requirement and the factors which influence the oxygen requirement. Equally important considerations which have received only limited attention are the environmental factors which affect bed dissipation. This is the area of concern of this research.

The sludge beds studied were located in the Lower Fox River. The Lower Fox River was chosen for its proximity to The Institute of Paper Chemistry and because of the large number of paper mills located along its length. From Lake Winnebago to its mouth at Green Bay, the Fox River is approximately 39 miles in length and is navigable by a system of 19 locks and dams. The elevation decreases 168.3 feet from Lake Winnebago at 745.1 feet above sea level to Green Bay at 576.8 feet. (A profile of the Lower Fox River is included in Appendix I.) This river has the heaviest concentration of paper manufacturing industry in the State of Wisconsin and receives waste discharges from eight municipalities and 18 pulp and paper mills. (A breakdown of the sources of input to the river and their locations is also given in Appendix I.) In addition, the river is used for hydroelectric power generation.

The flow of the Fox River is controlled by the U.S. Army Corps of Engineers through the operation of lake level control dams at Neenah-Menasha. No well-defined pattern of flow regulation is followed.

LITERATURE REVIEW

The literature associated with cellulosic sludge deposition and subsequent dissipation is, by nature of the complex phenomena, interdisciplinary and voluminous. This review organizes the literature around the following considerations: (1) oxygen uptake by benthal deposits; (2) bacterial degradation of cellulose; (3) anaerobic decomposition; and (4) sludge redistribution.

The phenomenon of sludge decomposition fits into nature's cycles as a part of the carbon cycle (1, 2). The carbon cycle is important because it is the means by which the energy of the sun is made available to organic life. Sludge decomposition serves as a medium for the replenishment of atmospheric carbon dioxide. The general problem of cellulose decomposition has been of interest since around 1900 (52, 53, 63).

OXYGEN UPTAKE CONSIDERATIONS

The physical picture of sludge decomposition which emerges from past studies is shown in Fig. 1 (3). There are two distinct zones of decomposition — an aerobic zone and an anaerobic zone. The aerobic zone has been of interest because of the effect it has on the oxygen balance in a river (4). This zone comprises only the very top layer of the sludge bed (approximately 1 cm.) (5, 6) while the anaerobic zone encompasses the remainder. The thickness of the aerobic zone is determined by a balance between the rate of diffusion of oxygen into the bed and the rate of its consumption by aerobic bacteria. Since the oxygen level of a river system is such an important water quality parameter, the oxygen uptake by benthal deposits has been extensively studied. Some of the parameters which have been examined for their influence on oxygen uptake are bed depth, oxygen level above the bed, pH, temperature, nutrients, invertebrate population, and the

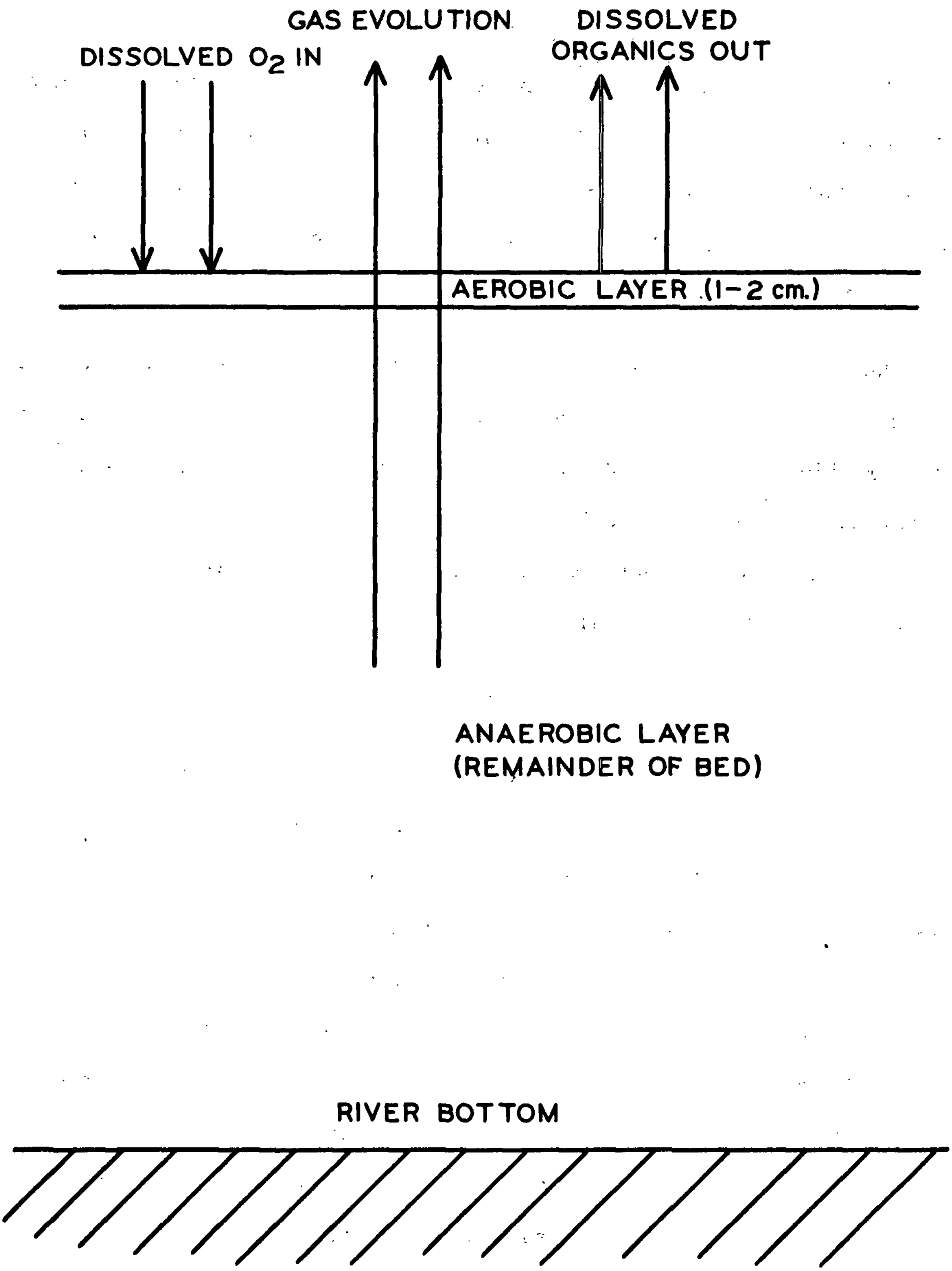


Figure 1. Schematic of Sludge Bed

age of the deposit (7-14). The oxygen demand of the bed is caused not only by uptake of oxygen by the bed but also by soluble material which leaches out of the bed (15), accounting in one case for 28% of the total demand (16).

Paper and board mill deposits have been investigated with respect to the parameters mentioned above (3, 17, 18). *In situ* benthal oxygen demand rates have even been determined for one particular sulfite mill's fiber deposits (19) and found to range from 3.60 g. $O_2/m.^2$/day when the deposit was undisturbed to 5.93 g. $O_2/m.^2$/day if dredged and resettled.

The Wisconsin Department of Natural Resources (DNR) developed a dissolved oxygen model for the Lower Fox River (20) and used as an uptake rate for beds 0.153 g. $O_2/m.^2$/day. The use of an oxygen uptake rate which is an order of magnitude different from that reported for similar streams indicates the existence of between-bed variation which makes generalization between river systems or possibly even between beds in the same river uncertain.

BACTERIAL DEGRADATION OF CELLULOSE

Both aerobic and anaerobic phases of cellulose decomposition are bacterial processes which depend on the presence of nutrients at beneficial levels, suitable temperature and pH, and the accessibility of the cellulose to the bacteria.

NUTRIENTS

Essential macronutrients include carbon, oxygen, nitrogen, hydrogen, magnesium, phosphorus, potassium, sulfur, iron, calcium, and trace metals (1, 21, 59). Sludge beds contain excessive amounts of carbon, but it might be anticipated that less than desirable amounts of nitrogen and phosphorus are present if the bed is the result of mill effluent (22, 57).

The levels of nitrogen and phosphorus required to sustain decomposition vary with the organisms involved but are generally of the same order of magnitude. Table I summarizes some of the nitrogen and phosphorus requirements given in the literature (1, 22-29). It can be seen that from 2 to 60 mg. of nitrogen and from 1 to 10 mg. of phosphorus per gram of cellulose are required for decomposition. The ratio of the amount of nitrogen to phosphorus required may be calculated from the average bacterial cell compositions as follows: The average phosphorus content of a bacterial cell is about 1.02% and the average nitrogen content is about 8.0%. So perhaps the phosphorus-nitrogen ratio should be about 1:8 (30).

The best source of nitrogen for anaerobic decomposition is ammonia (31, 38), but too large a concentration can be toxic. Table II gives a summary of McCarty's results on the effect of ammonia on anaerobic decomposition of sewage sludge (32).

The levels of trace metal ions required is a difficult question to answer because interactions occur between the various ions which stimulate or retard their effects (33). A rule of thumb based on experience in operating continuous anaerobic digesters is that the optimum concentration of monovalent metal ions occurs at approximately 0.01M and that of divalent metal ions at 0.005M (33). The question of salt toxicity has been a subject of active research (34, 35). Table III gives levels of trace metals required by the anaerobic bacteria found in the digestive tract of ruminants which decompose cellulose (31). Table IV gives trace metal ion levels required for the anaerobic decomposition of sewage sludge (32).

pH

A second factor which influences the bacterial degradation of cellulose is pH. Table V gives a summary of pH optima for some of the cellulolytic bacteria

(1). It appears that the pH must remain in the vicinity of seven for rapid decomposition to occur. The pH optima for cellulase enzymes are on the acid side, however, with animal cellulase optima in the region from 5.0 to 5.5 and those of bacterial cellulase from 5.8 to 7.0 (39).

TABLE I

LITERATURE DATA ON NITROGEN AND PHOSPHORUS
REQUIRED FOR CELLULOSE DEGRADATION

Literature Reference	Nitrogen Requirement (As Expressed in Ref.)	Phosphorus Requirement (As Expressed in Ref.)	N/G. Cellulose, mg.	P/G. Cellulose, mg.	Approx. P/N Ratio
Naoka, et al. (22)	C/N = 19 in theory; 28 to 36 in practice	C/P = 150	18	6.7	1:4
Speece and McCarty (24)	9 to 23 mg. N per g. COD	1/7 of N required	9 to 23	1.3 to 3.3	1:7
Sanders and Bloodgood (25)	N/C = 0.060 N/C = 0.024	-- --	4.56 1.86	-- --	-- --
Regan and Jeris (26)	C/N = 30 to 35	--	2.22 to 2.58	--	--
Siu (1)	1 g. N per 20 to 25 g. cellulose	--	18 to 40	--	--
Schroepfer and Ziemki (27)	1 g./20 g. BOD	1 g./100 g. BOD	50	10	1:5
Porges (23)	N/BOD = 1/17 N/COD = 1/25 C/N = 9.4/1	BOD/P = 90 to 150 P/C = 1/49 to 1/82	40 to 59	0.67 to 1.1	1:60
Sonoda and Ona (28)	0.05 volatile matter	0.01 volatile matter	50	10	1:5

TABLE II

EFFECT OF AMMONIA NITROGEN ON ANAEROBIC TREATMENT (32)

Concentration, mg./l.	Effect
50- 200	Beneficial
200-1000	No adverse effect
1500-3000	Inhibitory at high pH
3000-up	Toxic

TABLE III

RUMINANT BACTERIA TRACE METAL ION LEVELS

	Concentration	
Metal	Optimum, mg./l.	Toxic, mg./l.
S	10-500	1000
Ca	50-300	450
Mg	20-160	--
Mn	0-160	320
Fe	0- 50	300
Cu	0- 1	1.5
Co	0- 0.5	5
Zn	0- 0.05	5
B	0- 0	0.5

TABLE IV

SEWAGE SLUDGE TRACE METAL ION LEVELS

	Concentration, mg./l.		
Metal	Stimulatory	Noninhibitory	Inhibitory
Ca	100-200	2500-4500	8000
Mg	75-150	1000-1500	3000
Na	100-200	3500-5500	8000
K	200-400	2500-4500	12000
Soluble sulfide		50- 100	200

TABLE V

pH OPTIMA OF CELLULOLYTIC BACTERIA

Organism	pH Range Studied	pH Optimum
Bacillus thermofibrincolus	3.4-11.7	8.0-8.4
Bacterium protozoides	5.0-9.2	7.5
Cellulobacillus varsarviensis	5.8-8.15	7.5-7.7
Cellulomonas biazotea	5.2-6.9	6.4
Cellvibrio calida		7.8-8.1
Clostridium cellobioparus	4.0-8.0	5.5
Cytophaga hutchinsonii	6.5-9.0	7.5
Cytophaga polonicum	5.5-9.0	7.4
Cytophaga sp.	5.8-8.3	7.2
Itersonia ferruginea		6.5-8.0
Sorangium compositum	4.5-9.5	8.0-8.5
Sorangium nigrescens	4.5-9.5	8.0-8.5
Spirochaeta cytophaga	1.5-12.5	7.0-7.6
Sporocytophaga cytophaga	2.5-9.5	7.5
Sporocytophaga myxococcoides	5.7-8.5	5.6
Vibrio agarliquefaciens	4.6-7.6	7.6
Vibrio bulbosa	4.6-9.2	7.5-7.6
Vibrio napi	4.6-7.6	7.6
Vibrio pericoma	4.6-7.6	7.6
Vibrio prima	4.6-9.2	7.5-7.6
Vibrio sp.	2.5-9.5	7.7
Vibrio xylitica	5.0-9.2	7.5

The mechanism postulated for bacterial breakdown of cellulose is outlined in Fig. 2; this mechanism is the subject of active research with many questions still unanswered. Anaerobic decomposition consists of both a cellulose breakdown stage and an acid utilization stage. Both stages must operate efficiently or the decomposition will stop. If the acids are not utilized but rather allowed to accumulate, the pH drops and the cellulose breakdown ceases.

Anaerobic decomposition is characterized by mixed populations of bacteria (37) where one mixed population breaks down the cellulose, utilizing it for growth and reproduction and in the process producing organic acids, and another population of methane bacteria use the acids in their growth processes and produce

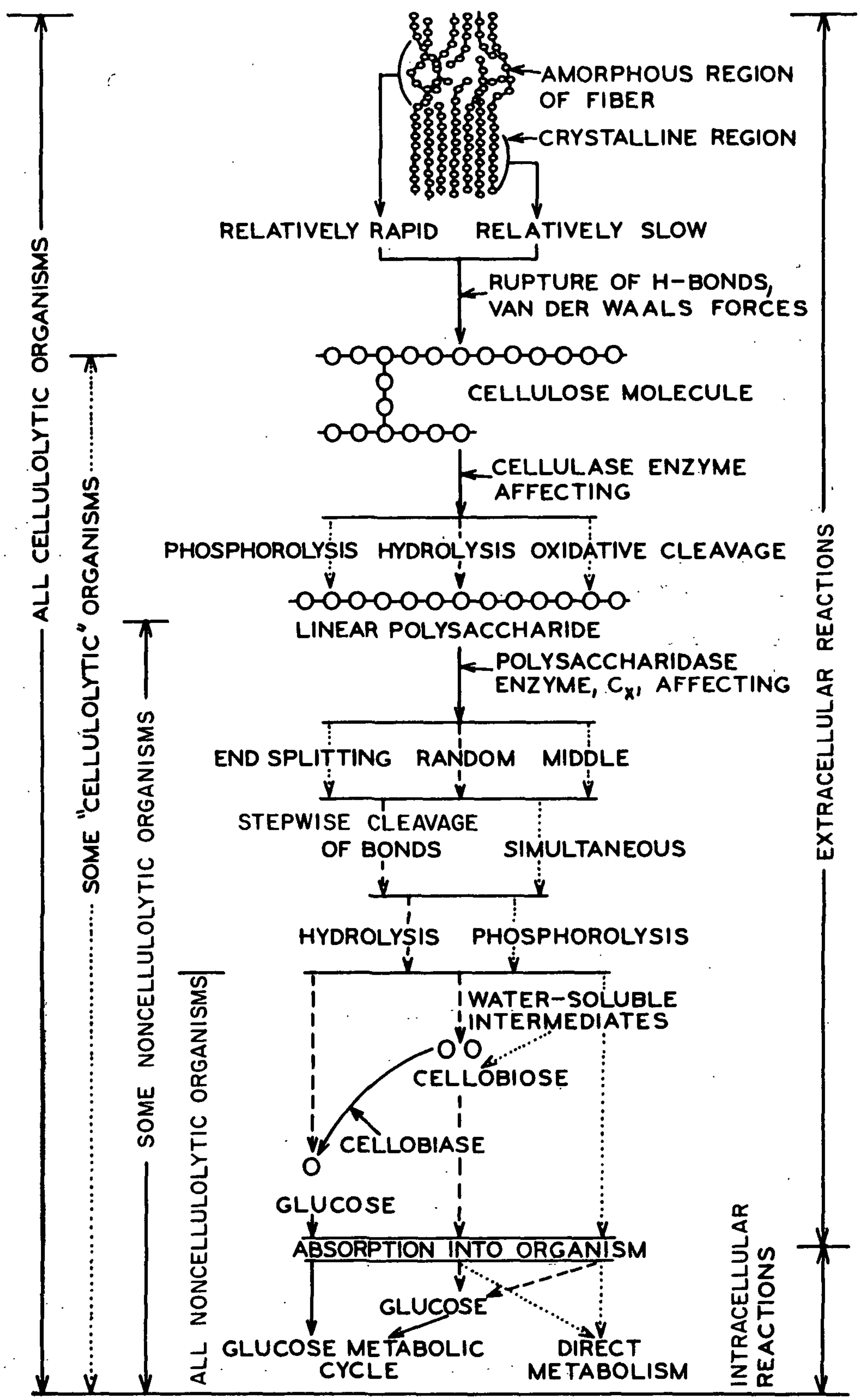


Figure 2. Biochemical Mechanism of Microbiological Breakdown on Cotton Fiber. Solid Lines, Experimentally Verified Steps; Broken Lines, Probable Steps; Dotted Lines, Speculative Possibilities [from (1)]

gas (36). This interdependence of populations for mutual benefit is called syntrophy. Methane bacteria have been investigated separately (41). The anaerobic decomposition of sewage sludge appears to be limited by this phase of the decomposition (40). Methane bacteria respond to pH as illustrated in Fig. 3; their pH optima are around seven (41).

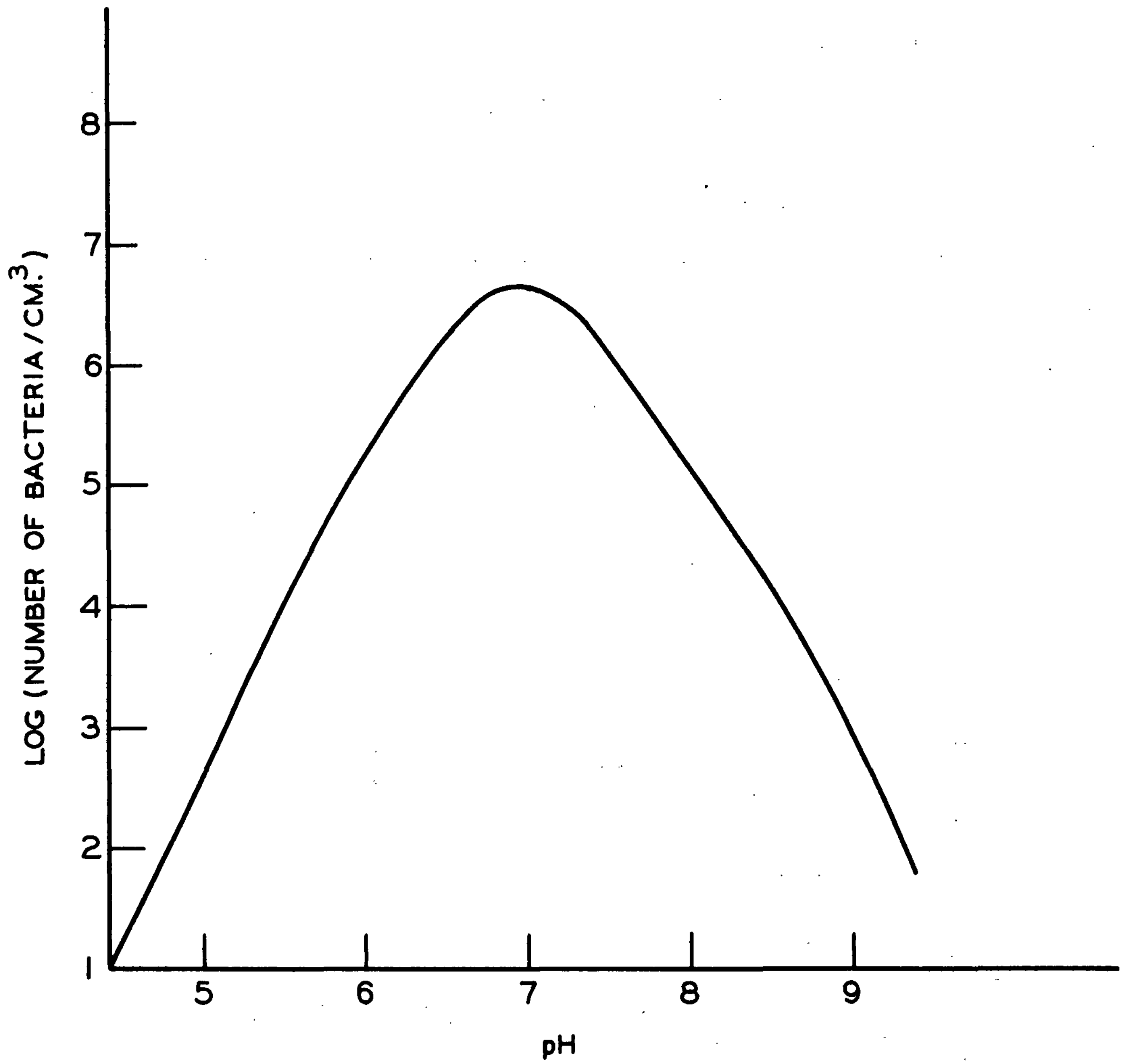


Figure 3. Effect of pH on Methane Bacteria Population (41)

TEMPERATURE

A third variable which affects the rate of cellulose decomposition is temperature. Bacteria are usually divided into three classes based on optimum growth temperatures, thermophilic bacteria from 45 to 70°C., mesophilic bacteria from 20 to 45°C., and psychrophilic bacteria from 10 to 20°C. (75). The conventional temperature range found in river systems, 1 to 30°C., suggests that most of the bacteria which have adapted to these conditions would be of the mesophilic or psychrophilic type. The psychrophilic type of bacteria has been studied very little; most of the anaerobic decomposition studies have used mesophilic or thermophilic types of bacteria. Table VI gives the optimum temperature for decomposition by some of the cellulolytic bacteria (1) and methane bacteria (41). The higher end of the range of temperature found in rivers seems more favorable for decomposition.

TABLE VI

TEMPERATURE OPTIMA OF CELLULOLYTIC BACTERIA

Organism	Temperature, °C. Range Studied	Optimum
Bacillus cellulosae-dissolvens	22 to 67	37
Bacillus thermofibrincolus	30 to 80	65
Bacteroides succinogenes	23 to 48	40
Cellulobacillus mucosus	15 to 46	37
Cellulobacillus myxogenes	15 to 46	37
Cellulobacillus varsarviensis	24 to 37	29
Cellulomonas biazotea	5 to 37	28
Cellvibrio calida		30-37
Cytophaga hutchinsonii		25-26
Cytophaga polonicum	2 to 30	23
Itersonia ferruginea	15 to 30	25-28
Microspira agar-liquefaciens	16 to 37.5	25
Pseudomonas fibrolysis	0 to 40	25
Sorangium compositum	7 to 42	34-35
Sorangium nigrescens	7 to 42	34-35
Spirochaeta cytophaga	20 to 35	30
Vibrio amylocella	15 to 42	37
Methane bacteria	20 to 35	28

The temperature behavior of sewage sludge decomposition has been studied extensively; the behavior appears to vary in different systems (43-48). For the anaerobic decomposition of one particular sewage sludge, a low-temperature threshold has been postulated (42). Figure 4 illustrates the presence of a 20°C. temperature threshold and a linear response to temperature reported for this particular sludge.

It has been postulated that both aerobic and anaerobic decomposition rates show Arrhenius temperature behavior over a limited range of temperature (such as from 10 to 25°C.) with the rate doubling every 10°C. for aerobic decomposition and increasing by 2.5 times every 10°C. for anaerobic decomposition (9). This assumption is incompatible with the postulated 20°C. temperature threshold.

The applicable temperature range for bacterial decomposition of cellulose could be limited by the temperature extremes at which cellulase enzyme denatures (40).

ACCESSIBILITY

Another factor which influences the rate of bacterial degradation of cellulose is its accessibility. The degree of crystallinity of the cellulose has been shown to affect significantly the rate of cellulase hydrolysis (76) and the rate of bacterial decomposition (49). It also has been demonstrated that the degree of lignification affects the rate of reaction (50). The higher the degree of lignification the slower the rate of bacterial decomposition. The process of anaerobic decomposition of cellulose is limited by the rate of cellulose breakdown (51), so accessibility is of importance in the river system.

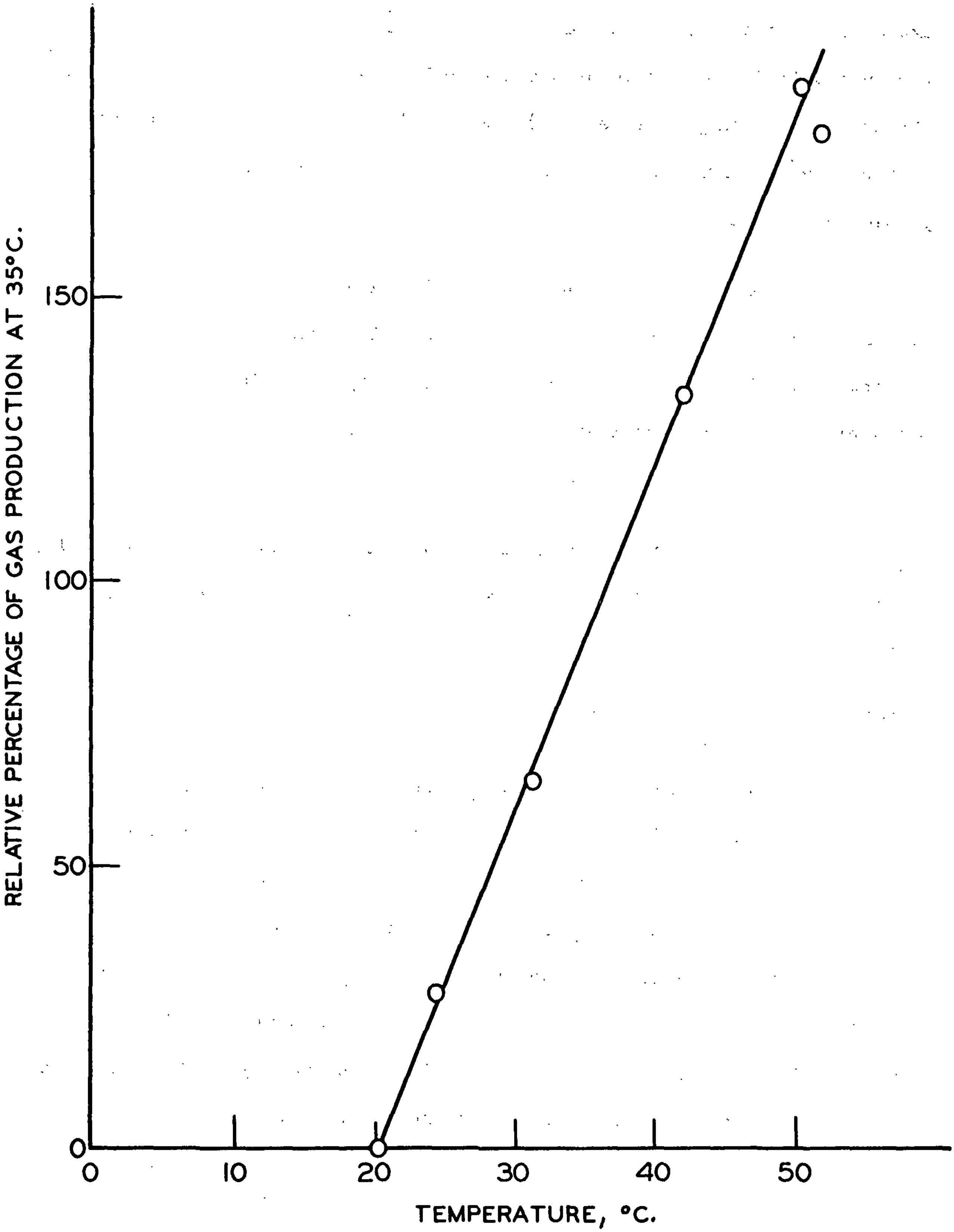


Figure 4. Relative Gas Production vs. Temperature

ANAEROBIC DECOMPOSITION

The overall physical phenomenon of anaerobic decomposition of wastes is quite well understood, but the specific biochemistry of the overall process is far from being fully elucidated (54, 55). The overall anaerobic decomposition process is illustrated in Fig. 5. Acetic, propionic, and butyric acids are the principal acids produced by cellulolytic bacteria, with acetic and propionic dominant (36, 40, 45, 54, 56, 58). The gases given off in anaerobic decomposition are mainly carbon dioxide and methane (36, 40, 45, 46, 56). In the anaerobic decomposition of carbohydrates the gas mixture is approximately half carbon dioxide and half methane (43, 56). The methane is produced by means of two distinct mechanisms, acid fermentation (e.g., CH_3COOH yielding CH_4 and CO_2) and carbon dioxide reduction (e.g., CO_2 and 8H yielding CH_4 and $2H_2O$) (40). The metabolic pathways involved in anaerobic decomposition have not yet been fully delineated (54).

Attempts made to develop kinetic models of the anaerobic decomposition process have been partially successful in predicting digester behavior (51, 60-62).

Anaerobic rates of decomposition of cellulose have been determined by others (64-66). Their results and the results of the present study are given in Table VII for comparative purposes.

SLUDGE REDISTRIBUTION

Although the description of sludge bed decomposition is the primary concern of this dissertation, attention is given to the problems of sludge flotation and sludge scour. It appears that sludge flotation has not been investigated previously, since the only literature located merely states that the problem exists in England in the spring of the year (67).

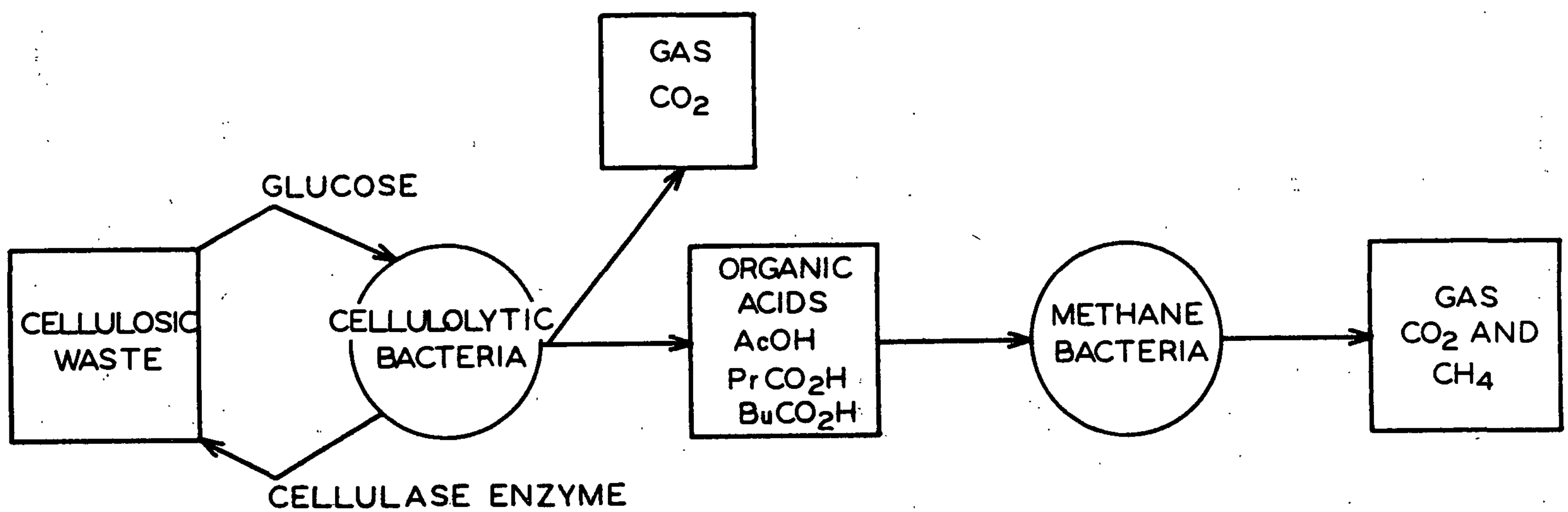


Figure 5. Qualitative Model of Anaerobic Decomposition

TABLE VII

SUMMARY OF DECOMPOSITION RATE OF CELLULOSE IN ANAEROBIC FERMENTATION

Authority	System & Culture	Initial Concn. of Cellulose	Cellulose Material	pH	Digesting Rate	Ref.	Remarks
Maki	Batch, mixed two pure cultures isolated from sewage digester, 38°C., mesophilic	2,000 mg./l.	Whatman's No. 1 filter paper	6.8	(1) 260 mg./l.-day (2) 660 mg./l.-day	64	Two exp. were made with different strains
Heukelekian	Batch, mixed culture from sewage digester, 25°C., mesophilic	3,120 mg./l.	Cellulose in sewage sludge	7.4	142 mg./l.-day	65	pH was maintained with lime
McBee	Batch, pure culture, isolated from soil and manure, 55°C., thermophilic	(1) 744 mg./l. (2) 2,980 mg./l.	Absorbent cotton	-- --	(1) 149 mg./l.-day (2) 426 mg./l.-day	66	Two exp. were made with different strains
Springer	Batch, mixed culture from fibrous river sludge, 25°C.	Approx. 20,000 mg./l.	Cellulose in fibrous river sludge	5.9-6.5	48 to 216 mg./l.-day		Range of rates of samples from monthly monitoring

The problem of scouring of mineral deposits has been investigated from the point of view of particle size and type of deposit (68). Tables VIII and IX summarize the results of this study. Since fibrous sludge beds contain a significant amount of fine sand and clay, they might be expected to experience scour in the velocity range from 1 to 2 ft./sec. Velz (69) studied the problem of scouring of sewage sludge river deposits and cited the following relation for predicting when scour of sewage deposits would occur:

$$V_c = [8Bg(s-1)d/f]^{1/2}$$

where V_c is mean channel velocity, f is the Weisback-Darcy friction factor, s is the specific gravity of the particle, d is the particle diameter, g is the acceleration due to gravity, and B is a constant whose value depends on the formation of the deposit and the state of consolidation. Values of B are from 0.22 to 0.06 for fresh deposits and 0.8 for consolidated deposits. The critical velocity range predicted for scour of sewage deposits was from 0.6 to 1.15 ft./sec. Therefore, a range of velocity which might reasonably be expected to produce scour of fibrous sludge beds is from 1 to 2 ft./sec., with perhaps the lower end of this range being sufficient.

TABLE VIII

MEAN CURRENT VELOCITY OF CLEAR AND MUDDY WATER REQUIRED TO INITIATE MOVEMENT ALONG A STREAM BED OF VARIOUS TYPES OF BOTTOM DEPOSITS
[Modified from Schmitz (1961)]

	Critical Mean Current Velocity			
	Clear Water		Muddy Water	
Type of Bed	cm./sec.	ft./sec.	cm./sec.	ft./sec.
Fine-grained clay	30	0.985	50	1.64
Sandy clay	30	0.985	50	1.64
Hard clay	60	1.97	100	3.28
Fine sand	20	0.657	30	0.985
Coarse sand	30-50	0.985-1.64	45-70	1.48-2.3
Fine gravel	60	1.97	80	2.63
Medium gravel	60-80	1.97-2.63	80-100	2.63-3.28
Coarse gravel	100-140	3.28-4.60	140-190	4.60-6.24
Angular stones	170	5.59	180	5.92

TABLE IX

FLOW VELOCITY REQUIRED TO MOVE MINERAL PARTICLES OF DIFFERENT SIZES
(from Nielsen)

Velocity, cm./sec.	Diameter of Mineral Particles, mm.
10	0.2
25	1.3
50	5.0
75	11.0
100	20.0
150	45.0
200	80.0
300	180.0

SCOPE OF THESIS

The three ways in which sludge beds dissipate: scour, flotation, and decomposition, are the main concerns of this investigation. Since scour and flotation remove material from a given site but not from the river system as a whole, the primary emphasis is given to the study of fibrous sludge bed decomposition.

Two types of decomposition can occur in a sludge bed, aerobic and anaerobic. The importance of aerobic decomposition in bed dissipation can be estimated from literature values of oxygen uptake rates. Since little information exists on anaerobic decomposition of cellulosic beds, this investigation concentrates mainly on anaerobic decomposition and the environmental factors which affect the rate at which it occurs. It first needs to be demonstrated that anaerobic decomposition of fiber is occurring in fibrous sludge. Then the effects of mass transfer characteristics, temperature, and nutrient levels are considered.

The approach used to investigate the fibrous sludge problem encompasses both field studies and laboratory studies. The field studies are of two types, surveys of the whole river and monthly monitoring of a single sludge bed site in the Lower Fox River. The purpose of the river surveys is to learn the extent of the sludge problem in the Lower Fox River and to observe variations in sludge bed properties with river position. Monthly monitoring of a single bed site gives the seasonal variations in sludge bed behavior and properties.

Laboratory studies are used to extend and quantify the knowledge gained from field observations, especially with regard to the rate of decomposition and the influences of various environmental factors. Two approaches are possible; laboratory experiments can be conducted using either a model sludge system or the river sludge itself. A model system is well-defined and reproducible, but results gained in this way are difficult to generalize to apply to the real system. The actual river sludge is not easily reproducible, but the results should be directly applicable to the Lower Fox River. The latter approach is used for this investigation. River sludge samples are studied under controlled laboratory conditions in a Warburg apparatus. It is hoped that the results obtained will be more meaningful in their application to the actual river system.

EXPERIMENTAL APPARATUS AND PROCEDURES

EQUIPMENT AND PROCEDURES FOR RIVER MONITORING PROGRAM

The river monitoring program included the following variables: sludge depth, core sample appearance, bed and water temperature, bed and water pH, dissolved oxygen content of the river water, sludge bacteria count, solids analysis, fiber analysis, and chemical analysis.

Bed depth was measured to determine if a bed at a given location exhibited a transient nature and how much variation in bed depth occurred with river position. Core samples were taken to see whether the beds were stratified. Temperature was selected as a variable because of its effect on the rates of chemical reactions which would be occurring if the beds were decomposing. pH monitoring of the water over the bed and of the bed interstitial water was conducted because of the important influence pH has on bacterial decomposition processes. The dissolved oxygen content of the river water over the bed was monitored because it is a common indicator of water quality and/or organic loading of the water. An attempt was made to obtain a representative number for total bacteria count because the amount of decomposition which occurs must be related to the bacterial population present. A sorting-out of the various populations was not attempted. Solids analyses were conducted to see if the amount of volatile matter in the bed increased or decreased as a proportion of the total matter between monthly bed visits and between river positions. Fiber analyses were carried out to see if a connection could be made between a river sludge deposit and the mill or mills which were located directly upstream from it. It was also hoped that these analyses would reveal if certain types of fiber or fiber cooked by certain processes decomposed more rapidly than others.

Chemical analyses of river water, sludge interstitial water, and sludge were carried out to establish the level of nutrients available for sustenance of decomposition. The following discussion gives detailed descriptions of the procedures used to evaluate each of the above parameters.

SLUDGE DEPTH DETERMINATION

In order to determine the depth of sludge deposits on the river bottom, a depth probe was constructed from two 2 in. by 2 in. by 15 ft. pieces of fir. One was sharpened and the other had a 10 in. by 12 in. foot. Both were marked in feet along their lengths. The procedure was to have both pieces flush to the foot, place the probe over the side of the boat perpendicular to the water, and lower it until the foot touched the top of the sludge. Then the pointed piece was pushed through the foot until it contacted the river bottom. The water depth and sludge depth could then be read from the scales on the probe, interpolating between scale markings with a one-foot ruler. Figure 6 is a sketch of this probe.

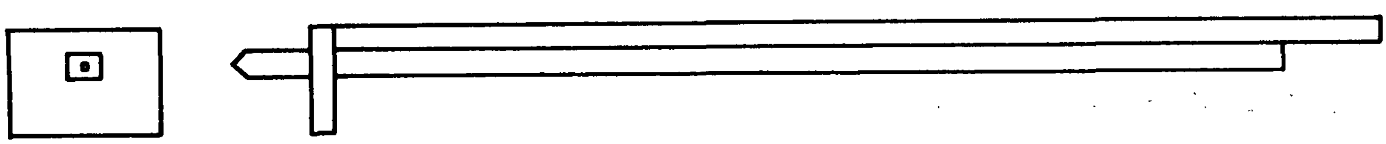


Figure 6. Sketch of Probe

CORE SAMPLES

A core sampler was constructed from an Ekman dredge and a 3 ft. by 6 in. by 6 in. Plexiglas box mounted on the end of an 18 ft. by 2 in. square staff, as sketched in Fig. 7. One side of the sampler is removable so that layers of a sample can be removed and separated. The sampler is tripped manually by a cord extending from the sides of the dredge to a common fitting and then up to the boat. The procedure used was to take a sample into the boat and photograph it while it was still in the sampler.

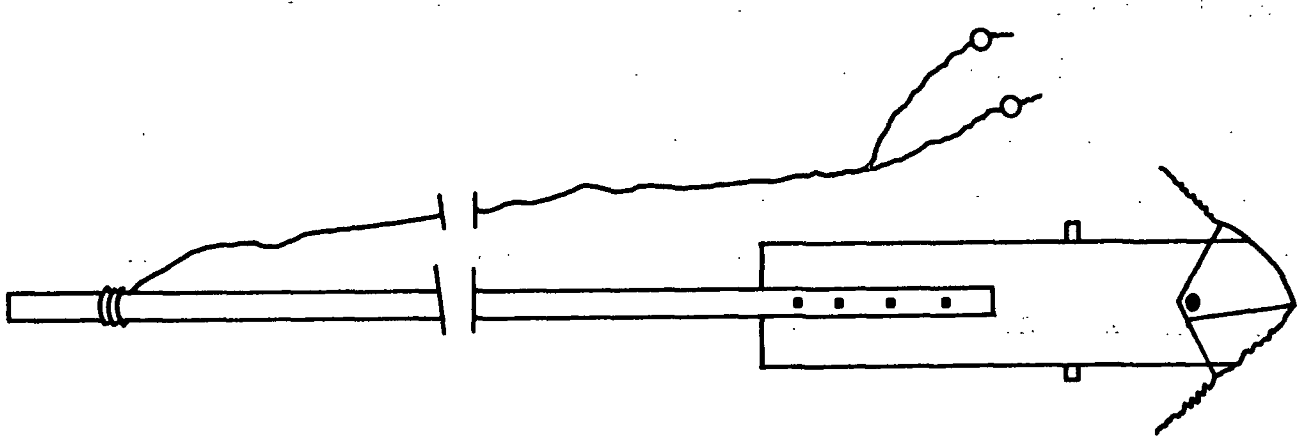


Figure 7. Core Sampler

BED TEMPERATURE DETERMINATION

A thermistor temperature probe was fabricated from an 18 ft. by 2 in. by 2 in. staff and six teflon-coated thermistors with 20-ft. leads. The six thermistors were placed six inches apart and protruded 1/2 inch from the wood. The probe is sketched in Fig. 8. The accuracy of the thermistors is ±0.5°C. The probe was inserted into the bed, equilibrated for five minutes, and then each thermistor was read using the YSI Model 46 TUC tele-thermometer. This probe was also used to measure the temperature of the water and the ambient air temperature.

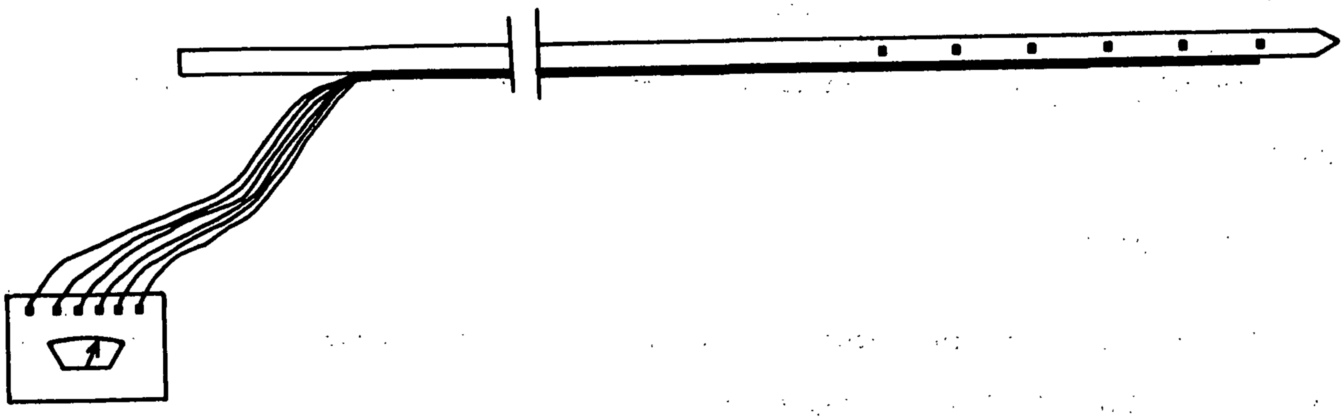


Figure 8. Thermistor Temperature Probe

SLUDGE SAMPLING

Samples of sludge material were collected using an Ekman dredge in the normal manner. The sample was transferred from the dredge to a 2-1/2-gallon stainless steel pail. After mixing well, two one-quart samples were taken and sealed in glass jars which were refrigerated upon return to the laboratory. The quart glass jars were prepared by rinsing with dilute HCl before leaving the laboratory and with river water before filling with the sludge sample. The samples collected were representative only of the top one to two feet of the sludge bed. Two quart samples of river water were also taken and handled in a similar manner.

TESTING OF SLUDGE SAMPLES

The sludge and river water were subjected to a variety of laboratory tests. The pH and dissolved oxygen were determined immediately upon return, approximately one hour after sampling.

pH DETERMINATION

The pH of the sludge and river water was measured using a Beckman Model 96 pH meter.

DISSOLVED OXYGEN

The dissolved oxygen content of the river water was measured with a Weston and Stack Model 300 dissolved oxygen probe.

BACTERIA COUNT

Bacteria counts were performed on the sludge samples using thioglycolate medium and the Most Probable Number (MPN) Method. All equipment was first sterilized. Test tube dilutions were prepared at 10^5, 10^6, 10^7, 10^8, and 10^9. At each dilution level, ten test tubes containing 1 ml. of the dilute bacteria solution and 9 ml. of broth were prepared and incubated at 35°C. for five days, after which the number of positive growth tubes at each dilution were counted. From a sequence of three dilutions which contained both positive and negative growth tubes, the bacterial population was calculated using the Halvorson-Ziegler probability tables (77).

This technique gives an estimate of bacteria, both aerobic and anaerobic, which can live on thioglycolate medium. The medium contains an oxygen scavenger, so the lower portion of each test tube is oxygen free. The count probably represents some of the cellulose-decomposing bacteria in the sludge system but does not detect the acid-utilizing methane bacteria. The technique also detects other bacteria present which can live on thioglycolate medium.

SOLIDS ANALYSIS

The total solids were determined by drying to constant weight at 105°C. The fixed solids were determined by ashing at 600°C. for two hours. The volatile solids are the difference between the total solids and the fixed solids. The quantity of volatile solids is taken as a measure of the organic content of the sludge. The actual organic content is less than the measured volatile solids because waters of hydration and some of the inorganic carbonate are also lost in the ashing process.

PERCENT FIBER ANALYSIS

An approximate determination of the amount of fiber present in the sludge was obtained through a series of filtrations. A 25-ml. sludge sample was placed on a No. 70 screen (0.0083-in. openings) and washed with two gallons of water; the material remaining on the screen was subjected to a solids analysis. The material washed through this screen by the two gallons of water was strained through a No. 140 screen (0.0041-in. openings); the material retained by this screen was subjected to a solids analysis. The final filtration was through Whatman's No. 40 ashless filter paper, and the material retained by it was also subjected to a solids analysis. Microscopic examination revealed that the majority of the fiber was retained on the No. 70 screen and a small amount on the No. 140 screen. The quantity

$$100[(VS_{\text{No. }70} + VS_{\text{No. }140})/(TS_{\text{No. }70} + TS_{\text{No. }140} + TS_{\text{filter paper}})]$$

was defined as percent fiber.

FIBER COMPOSITION

Portions of each sludge sample were given to the Fiber Microscopy department for fiber composition and fiber length analyses and photomicrographs at 35X, 125X, 185X, and 465X. The procedure used to determine fiber composition was as follows.

<u>Sampling and Dilution</u>

Two sampling techniques were used, oven-dried and freeze-dried. Once the samples were dried, the same method was used to dilute each sample. Two-tenths gram of dried sample was dispersed in 200 cc. of distilled water. One cc. was removed from each suspension and evaporated to dryness in a one-square-inch area on a standard glass slide.

<u>Staining and Counting</u>

The one-square-inch area on the glass slide was stained and mounted in "C" Stain. A point counting system was employed by counting and recording each type of material as it passed the eyepiece pointer in a horizontal direction. After counting one line the stage was moved 4 mm. vertically to a new line and the counting repeated. This procedure was continued until five separate lines, each 4 mm. apart, had been examined. Two one-square-inch fields were examined for each sludge sample. Suitable weight factors were applied to each type of material. Since there are no established relative weight factors for algae, a factor based on the dimensions and cell-wall thickness of the cells was used. The weighted percentages of each material present were calculated.

FIBER LENGTH

Sampling and Dilution

A representative amount was removed from the sludge sample and dispersed in distilled water in a 500-ml. Erlenmeyer flask. This suspension was divided into six large test tubes. Each suspension was individually diluted to the desired consistency. Several ml. were removed from each suspension and dried on a 1 by 2-in. area of a standard microscope slide.

Staining

The slides were then stained and mounted in "C" Stain. Approximately 800 fibers are measured by the following procedure.

Measurements

A stained fiber slide is projected from below upon a screen, using 50X magnification. The lengths of the fibers are measured from the projected image by tracing from one end of the fiber to the other with the rotating wheel of a curvimeter. At the end of the fiber, the push lever of the curvimeter is depressed and the curvimeter raised a little. This movement imparts an impulse which records the fiber in the proper length group.

The recorder does the following during the process of measurement: (1) It divides the measured fibers into length groups, and tabulates the number of fibers in each group. The span of a group is 0.2 mm. with the exception of the first group, which is 0.1 mm. The Institute model has been constructed for a maximum fiber length of 6.9 mm. (2) It gives the total number of the measured fibers.

The projector has a rotating object stage. To facilitate measuring the field of view, a circular glass plate 2 cm. in diameter and divided into 12 sectors and an inner circle, is attached in the center of the object stage, 0.2 mm. below the slide.

On the sloping measuring table there is a glass plate of 72 cm. x 47 cm., which is covered with a translucent plastic drawing foil to prevent slippage of the curvimeter wheel.

All fibers in a field of 2-cm. diameter are measured with the curvimeter, including any crossing the outer circle when more than half of their lengths lie within the line.

The recorder automatically gives the number of fibers in every length group and the total number of the measured fibers. These data, plus average of length interval in mm., percentage of fibers by number, percentage of length per interval, arithmetic average fiber length, and weighted average fiber length, are tabulated by the computer.

CHEMICAL ANALYSES

Portions of each sludge sample were also analyzed by the Analytical Chemistry Department for nitrogen in various forms, phosphate, mercury, and other trace metal ions.

Nitrogen Analyses

The methods used were taken from the 12th and 11th editions of "Standard methods for the examination of water and waste water" (78, 79). Ammonia was determined by the distillation method (p. 391) and the organic nitrogen by the Kjeldahl method (p. 402), both from the 12th edition. The methods of analysis for nitrate by the phenoldisulfonic acid method (p. 180) and nitrite (p. 175) were taken from the 11th edition.

Phosphate Analysis

Phosphate was determined by the stannous chloride method for orthophosphate (79, p. 202).

Mercury

The mercury analysis was performed according to the Federal Water Quality Administration proposed method for mercury in bottom muds. A 0.5-g. sample was weighed into a 50-ml. Erlenmeyer flask, and 5 ml. of concentrated hydrochloric acid and 1 ml. 6% (or 5%) W/V potassium permanganate were added. The flask was placed in an automatic shaking water bath for two hours at 58°C. The contents were then transferred into a 250-ml. Erlenmeyer flask, using 95 ml. of distilled water; 50 ml. of reductant was added, the sparge was attached, and the mercury measurement was performed as described in the General Procedure (74).

Trace Metal Ions

Analytical Group Method 62 for emission spectrographic analysis was used to determine the trace metal ions magnesium, calcium, iron, aluminum, silicon, lead, zinc, sodium, titanium, copper, manganese, potassium, and phosphorus.

Chemical Oxygen Demand

In order to be able to calculate aerobic estimates of sludge bed life, the COD of several sludge samples was determined by the dichromate reflux method (78, p. 510).

LABORATORY TECHNIQUES FOR STUDYING SLUDGE DECOMPOSITION

The experimental techniques developed can be rationalized in terms of the qualitative model for anaerobic decomposition shown in Fig. 5 of the Literature Review (p. 18).

The basic technique used to study the anaerobic decomposition of sludge samples employed the Warburg apparatus, in which the gas produced in a sealed, oxygen-free system can be monitored as the pressure increase registered on a mercury manometer. Gas produced was analyzed for nitrogen, carbon dioxide, and methane using gas chromatography. At the end of a Warburg run the sludge remaining in the flask was analyzed for solids (in the manner described above), glucose, and organic acids. Glucose and organic acids are intermediates in the anaerobic decomposition process.

In order to demonstrate that fibers were experiencing anaerobic decomposition, ^{14}C-labelled fibers were added to Fox River sludge and the mixture studied using the Warburg technique. To detect ^{14}C-labelled carbon dioxide in the gas produced, a technique was developed to absorb the carbon dioxide and count the radioactive decay by means of scintillation.

WARBURG TECHNIQUE

The conventional Warburg apparatus (<u>80</u>) was used to determine the rate of anaerobic decomposition of river sludge samples in a batch process. Mercury was used as the manometer fluid. The 125-ml. Warburg flasks with a single side-arm with ground-glass stopper were first sterilized. To each flask were added 50 ml. of river sludge and 20 ml. of sterile distilled water. A special 50-ml. cylindrical scoop was devised for measuring the sludge, consisting of a stainless steel cup with a handle whose volume was precisely 50 ml. The cup was first filled to overflowing with sludge and then the excess scraped off with a straight edge.

After the flask was charged, it was attached to the manometer and placed in the water bath. Air was purged from the flask and manometer by flushing for three to five minutes with nitrogen gas filtered through sterile glass wool. The system was sealed and allowed to come to thermal equilibrium (15 minutes), after which the manometer was relieved and resealed.

The rate of gas production was measured by the rate of pressure build-up, which was monitored and released at fixed time intervals, usually one or two days, by drawing off the gas produced with a gas syringe. The gas composition was analyzed using gas chromatography. After monitoring for the desired time interval, the flasks were removed from the apparatus and the contents analyzed for pH, total solids, volatile solids, fixed solids, glucose, and organic acids. Sometimes photomicrographs of the flask contents were taken. The recorded gas pressures can be converted to volume of gas produced if the composition of the gas is known.

GAS ANALYSIS

Gas chromatography was used to analyze the gases evolved during sludge decomposition. An eight ft. by 1/4-in. Porpack Q (Waters Associates) column made the desired separation. The conditions used were: column at 100°C., injector at 150°C., thermal conductivity detector at 150°C., thermal conductivity detector current at 100 ma., and helium flow rate of 50 cc./min. The chromatograph was directly calibrated for the three gases of interest by injecting known quantities of each gas and measuring the response at 64X amplification. The peak areas were calculated as peak height times width at half height. Figures 9, 10, and 11 give the calibration curves for methane, carbon dioxide, and nitrogen, respectively. A representative chromatogram is shown in Fig. 12.

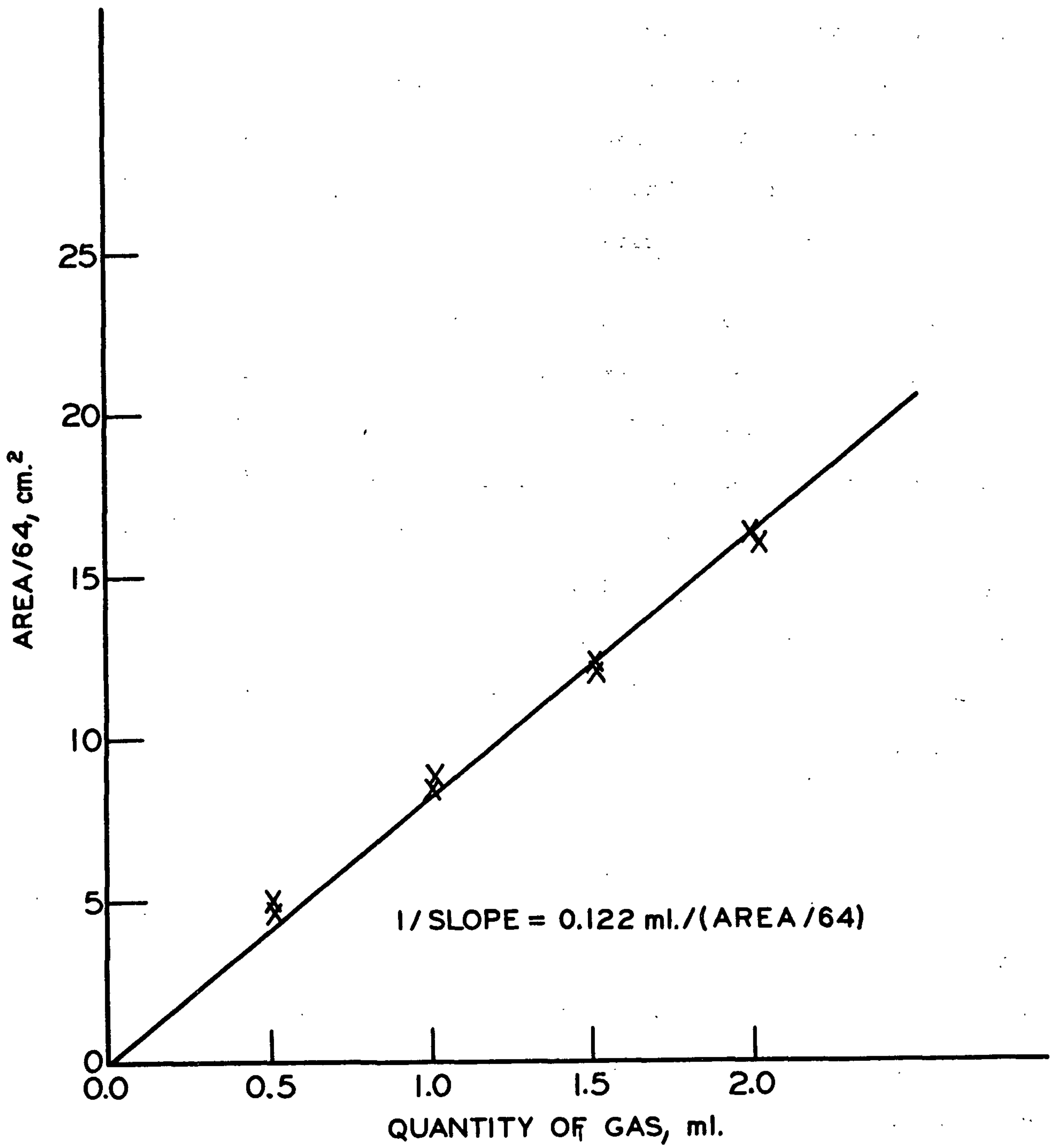


Figure 9. Methane Calibration Curve

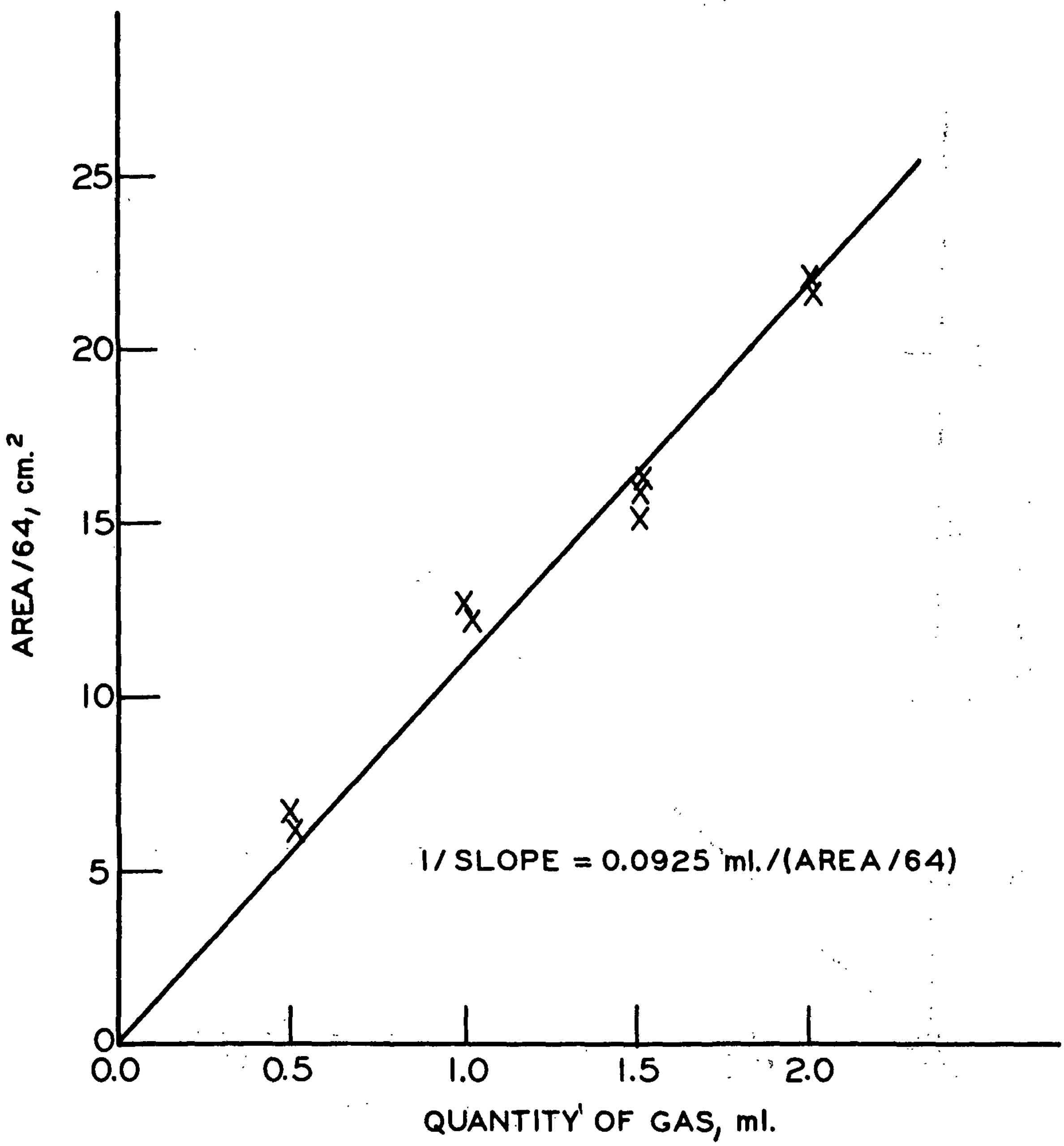


Figure 10. Carbon Dioxide Calibration Curve

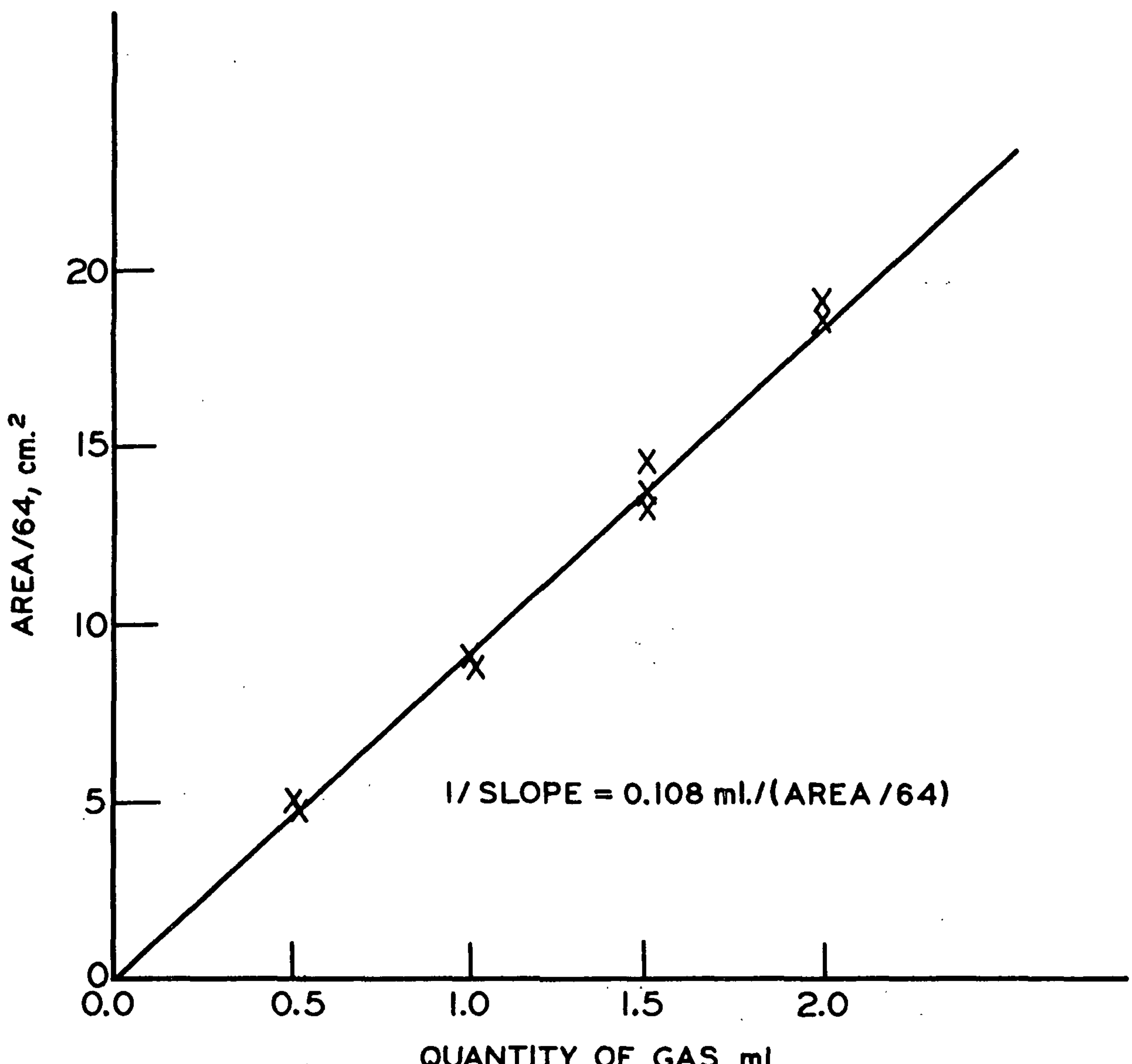


Figure 11. Nitrogen Calibration Curve

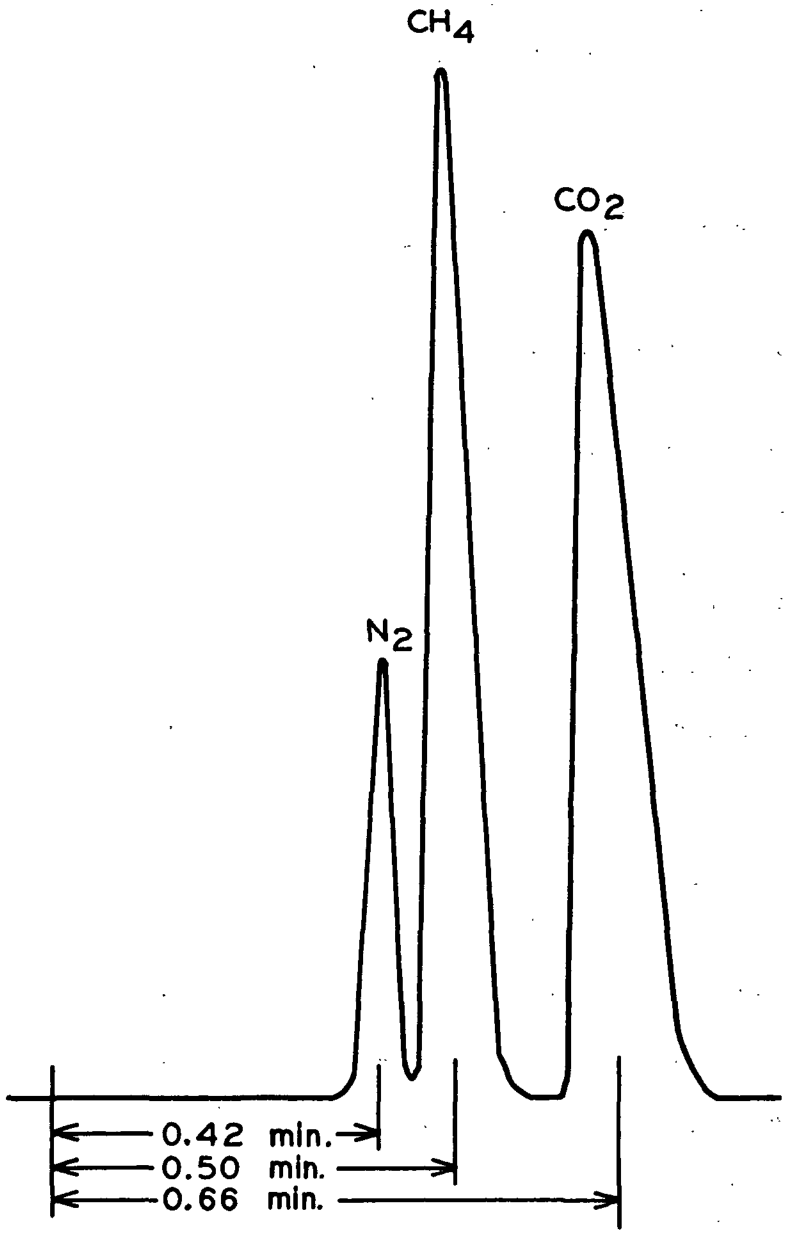


Figure 12. Representative Gas Chromatogram Obtained in Gas Composition Analysis

GLUCOSE ANALYSIS

Glucose was analyzed by an enzymatic procedure marketed by Worthington Biochemical Corp. under the trade name Glucostat. The test is based on the reaction scheme:

$$\text{glucose} + O_2 + H_2O \underset{\text{(glucose oxidase)}}{=} H_2O_2 + \text{gluconic acid}$$

$$H_2O_2 + \text{reduced chromogen} = H_2O + \text{oxidized chromogen}$$

The reaction was monitored spectrophotometrically at 400 nm. on the Cary Model 15 Spectrophotometer.

Analyses performed using standard glucose solutions gave a standard deviation of the regression of 0.027. The 95% confidence limits for the determination of the glucose concentration from absorbancy measurements was ±0.003 g./l. The concentration is calculated as

$$\text{conc.}_{\text{unk.}} = \text{conc.}_{\text{std.}}(\text{abs.}_{\text{unk.}}/\text{abs.}_{\text{std.}}).$$

Analyses performed on samples consisting of sludge interstitial water plus a known quantity of glucose gave the expected results within the experimental error limits of the test, indicating that other materials present are not interfering with the test.

ORGANIC ACID ANALYSIS

Gas chromatography was used to analyze for the amounts of acetic, propionic, and butyric acids present. A 10 ft. by 1/8-in. stainless steel column packed with 20% free fatty acid polymer (FFAP) on Chromosorb W was used. The experimental conditions were: column at 160°C., injector at 200°C., detector at 200°C., hydrogen pressure of 12.5 p.s.i., and nitrogen flow rate of 85.7 cc./min. Amyl alcohol was used as the internal standard. The standard deviations of the regression and the confidence limits are given in Table X for the calibration curves which are shown in Fig. 13. A typical chromatogram is shown in Fig. 14. The peak for acetic acid starts at 7 min., that for propionic acid at 9.5 min., and that for butyric acid at 14 min. for this column at the conditions used. Usually from 3 to 5 µl. of sample was injected; 10 ml. of the sample contained 1 µl. of amyl alcohol as internal standard. A chart rate of 1/2 in./min. was used, and the amplifier was set at 1 x 8 or 1 x 16.

TABLE X

STATISTICS FOR ACID CALIBRATION CURVES
(Figure 13)

Acid	Number of Points in Regression	Standard Deviation of Regression	95% Confidence Limits in Determining Acid Quantity from Area
Acetic	8	0.0538	±0.48 to ±0.51
Propionic	8	0.0567	±0.30 to ±0.33
Butyric	8	0.0612	±0.24 to ±0.44

RADIOACTIVE COUNTING TECHNIQUE

The radioactive carbon dioxide produced in the experiments designed to prove cellulose decomposition was detected by a scintillation counting technique. The $^{14}CO_2$ was withdrawn from the Warburg flask and injected into a flask with an expandable seal which contained either 5 or 10 ml. of NCS solubilizer (70), a quaternary ammonium base in toluene, for absorbing the gaseous CO_2. The sealed flask was placed on a slow shaker at room temperature and shaken for 24 hr. to allow time for the absorption of the CO_2. Three ml. of the NCS containing the

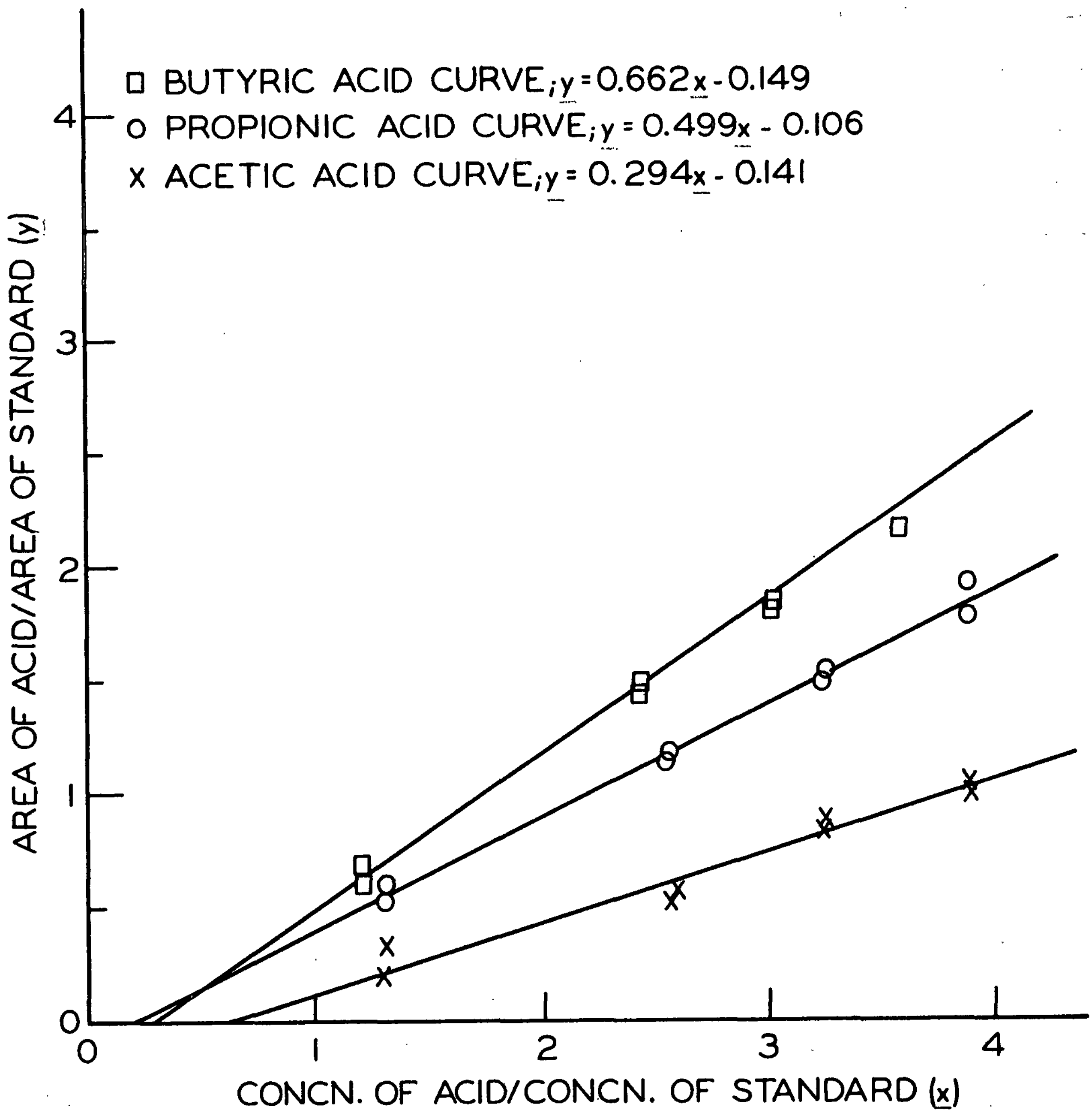


Figure 13. Calibration Curves for Organic Acids Determinations by Gas-Liquid Chromatography

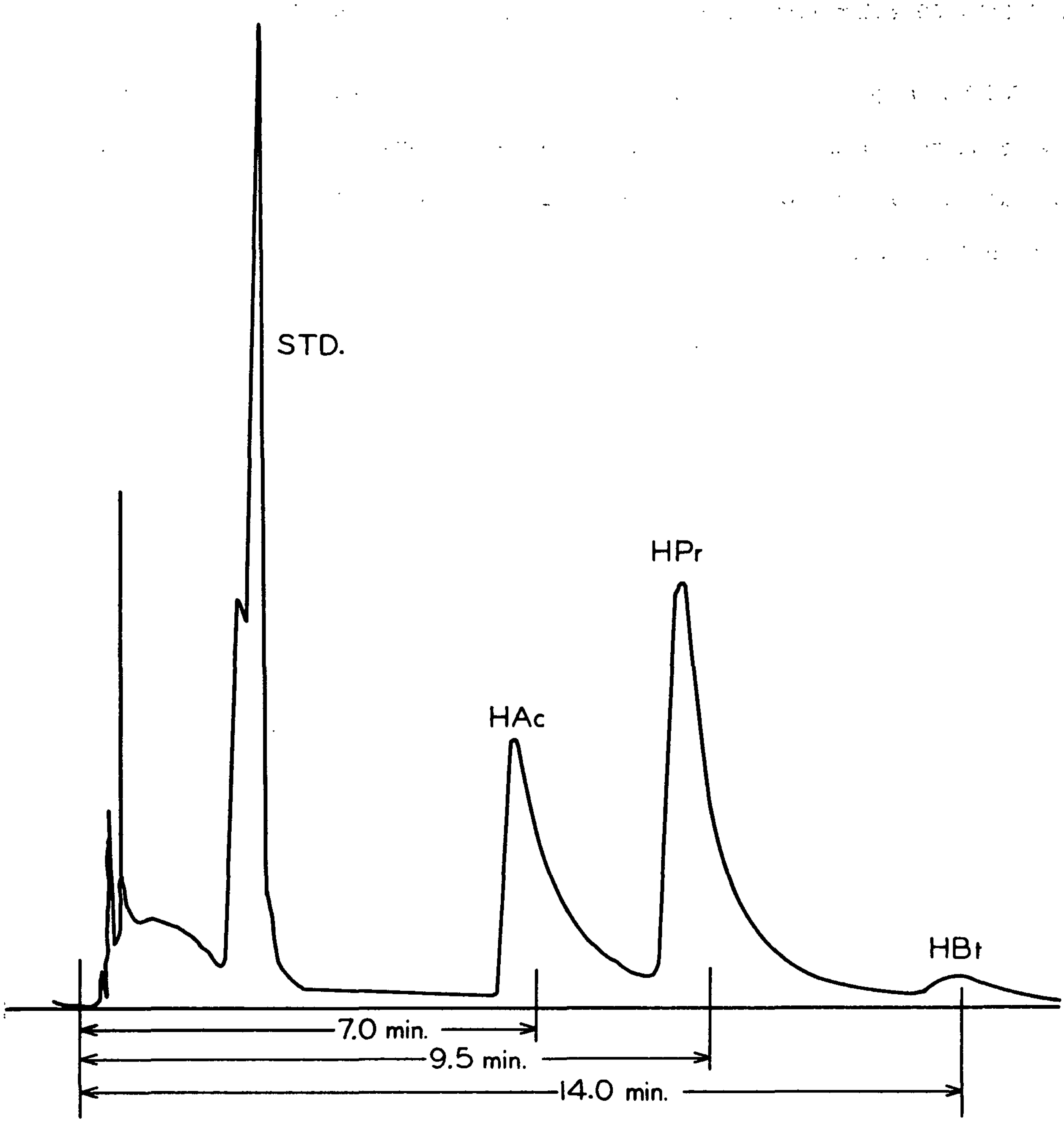


Figure 14. Organic Acids Chromatogram, River Sample SXIII Interstitial Water

absorbed CO_2 were then mixed with 15 ml. of Cocktail T [1000 ml. toluene containing 5 g. 2,5-diphenyloxazole (PPO)] and counted at 2% error on the Beckman Model DPM-100 scintillation counter using the ^{14}C-only window.

NCS has a quenching effect on the count, so a quench curve was constructed by varying the amount of NCS in the sample and determining the corresponding external standard ratios in order to correct for this effect. This quench curve is given in Fig. 15.

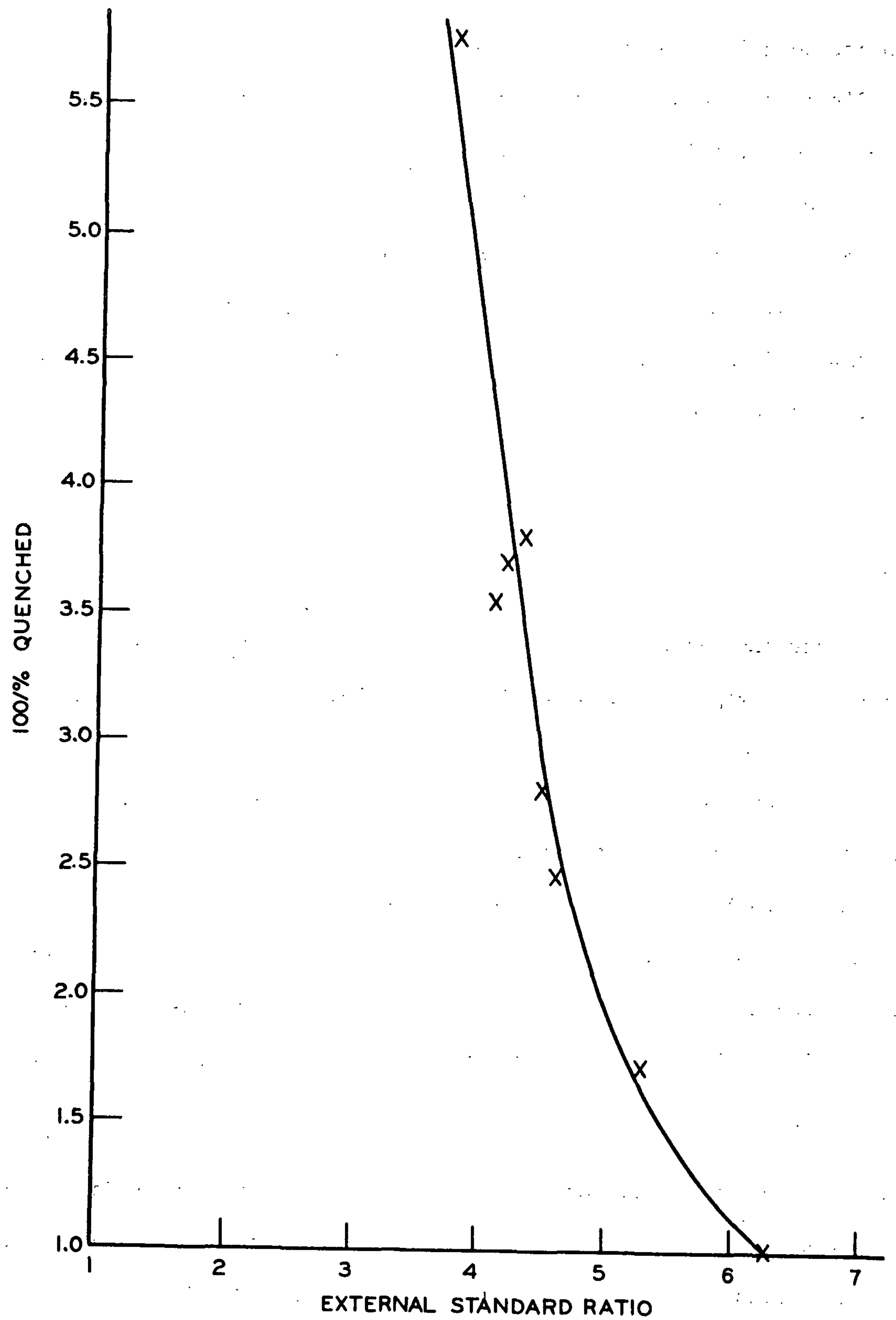


Figure 15. NCS Quench Curve (^{14}C-Only Window)

RESULTS AND DISCUSSION

In order to gain a better understanding of the sludge problem in the Lower Fox River, two phases of study were pursued, a field phase and a laboratory phase. The field investigation in turn consisted of two parts, river surveys to determine the extent of the problem and to note differences among the different positions in the river, and a program of monthly monitoring of a single bed to determine its changes throughout a yearly cycle. The laboratory phase concentrated on exploring the effects of various environmental factors on the anaerobic decomposition of fibrous sludge.

FIELD STUDIES

RIVER SURVEY

To discover the extent of the sludge problem in the Lower Fox River, an extensive river survey was conducted in June, 1970, with additional surveys in November, 1970 and July, 1971 to complement the first survey. The surveys consisted of measuring the physical and chemical characteristics of sludge deposits in the Lower Fox River. The data from these surveys are summarized in Fig. 16 and Tables XI through XVII. In addition to these data, 35-mm. slides were taken of core samples of sludge and photomicrographs at 35X, 125X, 185X, and 465X were made of sludge samples. These slides and photomicrographs have been placed on permanent file at The Institute of Paper Chemistry and are not included in this dissertation.

Figure 16 shows the state of sludge distribution in the Lower Fox River at the time of the June, 1970 survey. Approximately half of the river bottom was covered with fibrous sludge. A fibrous sludge bed was defined as a sediment depth of at least six inches with the sediment containing more than 5% fiber by

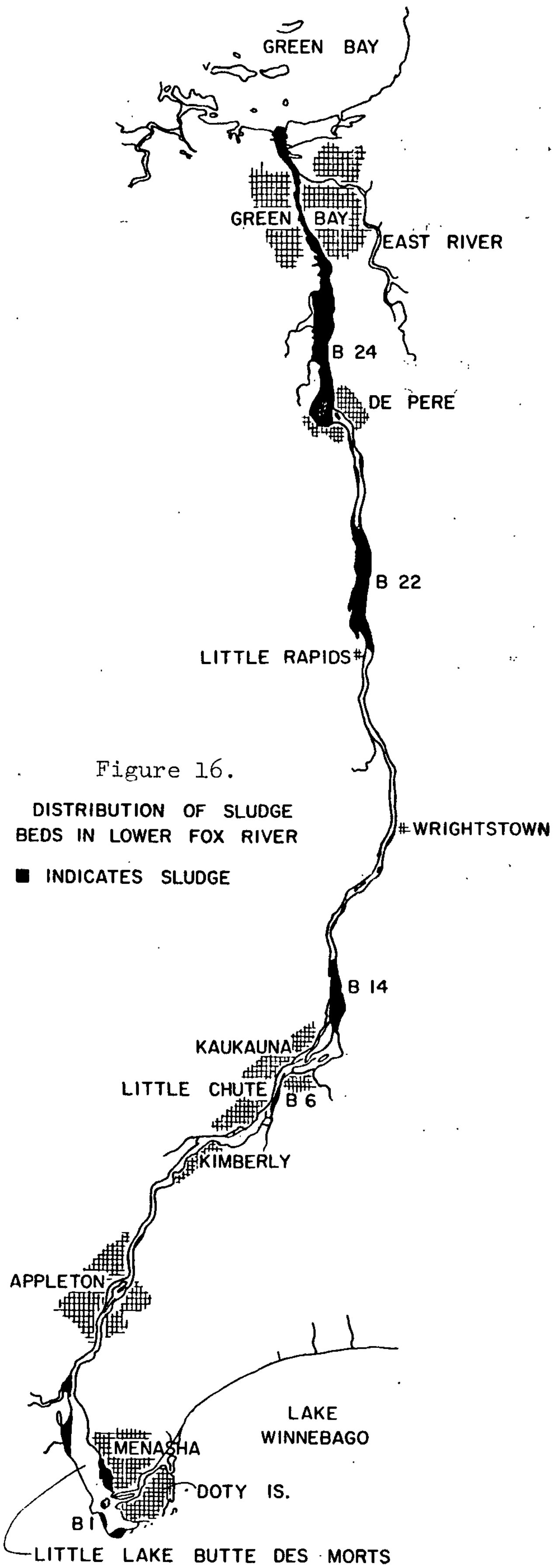


Figure 16.

DISTRIBUTION OF SLUDGE BEDS IN LOWER FOX RIVER

■ INDICATES SLUDGE

TABLE XI

FIELD DATA FROM RIVER SURVEY
JUNE 1970

Bed[a]	Ambient Temperature, °C. ±0.5[b]	Water Temperature, °C. ±0.5[b]	Bed Temperature $1\frac{1}{2}$' Below Surface, °C. ±0.5[b]	Water Depth ±2"[b]	Sludge Depth ±2"[b]	Water Above Bed: Dissolved Oxygen, p.p.m. ±0.1[b]	Water Above Bed: pH ±0.1[b]	Sludge pH ±0.1[b]
B 1	24.6	22.6	19.4	4'10"	2'6"	8.9	7.6	5.9
B 2	24.6	22.6		4' 6"	6"	9.2	9.0	5.1
B 3	24.8	23.0	18.0	7'	2'	9.8	9.2	6.5
B 4	22.1	22.3	18.0	6' 6"	3'	10.2	9.2	6.4
B 5	23.8	22.8	17.6	5' 3"	5'6"	6.2	8.3	6.8
B 6	28.8	24.2	20.2	3' 6"	3'	6.2	8.7	6.3
B 7	28.8	24.2	20.6	3'	3'	7.2	8.9	6.2
B 8	31.8	24.2	22.2	3'	5'+	7.6	8.7	6.5
B 13	29.8	25.4	19.4	5'	5'+	5.9	8.6	6.6
B 14	31.8	23.6	20.2	4' 6"	5'+	8.9	9.0	6.6
B 17	34.4	26.8	19.4	3'	2'	8.9	8.9	6.6
B 18	20.8	22.8	17.8	2'	5'+	6.9	8.4	6.2
B 22	27.0	25.2	22.0	6'	5'+	6.4	8.6	6.3
B 23	23.6	24.2	19.4	3'	3'	7.0	8.7	6.3
B 24	25.0	23.9	20.9	2' 6"	5'+	7.2	8.6	6.4
B 25	16.4	21.2	18.1	6' 6"	5'+	6.4	7.9	6.7
B 26	19.0	23.2	18.9	7'	5'+	1.4	8.7	6.7

[a] The bed numbers represent actual locations in the Lower Fox River where the samples were collected. The numbers increase downstream, starting with B1 in Little Lake Butte des Morts and ending at the river mouth at Green Bay. Some of these locations are indicated on Fig. 13.

[b] Standard deviation of measurement.

TABLE XII

GLUCOSE ANALYSIS OF SAMPLES FROM
FIVE LOWER FOX RIVER SLUDGE BEDS
JUNE 1970

Bed	Water Over Bed, g./l. ±0.003[a]	Interstitial Water, g./l. ±0.003[a]
B 1	0.003	0.000
B 6	0.000	0.002
B 14	0.000	0.006
B 22	0.000	0.005
B 24	0.002	0.001

[a]95% Confidence limits.

TABLE XIII

BACTERIA COUNTS OF SAMPLES FROM
FIVE LOWER FOX RIVER SLUDGE BEDS
JUNE 1970

Bed	Number/Ml. ±10%[a]
B 1	3.8×10^6
B 6	1.13×10^6
B 14	1.1×10^6
B 22	0.18×10^6
B 24	0.19×10^6

[a]Standard deviation.

TABLE XIV

A. CHEMICAL ANALYSES OF WATER SAMPLES FROM FIVE SELECTED LOWER FOX RIVER SLUDGE BEDS
JUNE 1970

	Total Kjeldahl Nitrogen, mg./l.	Free Ammonia, as NH_3, mg./l.	Nitrate, as NO_3, mg./l.	Nitrite, as NO_2, mg./l.	Phosphate, as PO_4, mg./l.
Water Over Top of Sludge					
Sample BW 1	0.11	0.31	0.39	0.01	0.18
Sample BW 6	2.38	0.17	0.29	0.01	0.01
Sample BW 14	0.41	0.55	0.58	0.02	0.05
Sample BW 22	0.45	0.68	0.54	0.01	<0.01
Sample BW 24	0.47	1.42	0.44	0.01	0.05
Sludge Interstitial Water					
Sample BIW 1	0.64	26.7	4.6	0.33	0.07
Sample BIW 6	0.70	15.6	0.30	0.17	0.09
Sample BIW 14	0.82	0.95	19.3	61.0	<0.01
Sample BIW 22	1.44	0.33	71.3	0.04	0.30
Sample BIW 24	0.26	0.58	190[a]	0.03	0.08

[a]An average of two determinations.

TABLE XIV (Continued)

B. CHEMICAL ANALYSES OF DEWATERED SLUDGE FROM FIVE SELECTED LOWER FOX RIVER SLUDGE BEDS JUNE 1970

Sludge Samples	Solids, %	Total Kjeldahl Nitrogen, %	Free Ammonia, as NH_3, %
Sample B 1	22.87	0.89	0.02
Sample B 6	39.99	0.47	0.008
Sample B 14	44.54	0.45	0.01
Sample B 22	39.12	0.47	0.02
Sample B 24	32.51	0.94	0.06

Note: Unless otherwise indicated, all values represent single determinations.

TABLE XV[a]

FIBER ANALYSIS OF SAMPLES FROM FIVE SELECTED
LOWER FOX RIVER SLUDGE BEDS
JUNE 1970

Identification	Sample B 1			Sample B 6		
	Field 1	Field 2	Total	Field 1	Field 2	Total
Hardwood cold soda or chemigroundwood	--	--	--	5	6	11
Softwood chemical (kraft and sulfite)	--	1	1		1	1
Hardwood kraft	--	--	--	--	--	--
Filamentous algae	3	2	5	19	21	40

Identification	Sample B 14			Sample B 22			Sample B 24		
	Field 1	Field 2	Total	Field 1	Field 2	Total	Field 1	Field 2	Total
Hardwood cold soda or chemigroundwood	1	1	2	1	1	2	1	3	4
Softwood chemical (kraft and sulfite)	1	--	1	--	--	--	1	--	1
Hardwood kraft	--	1	1	1	--	1	1	--	1
Filamentous algae	5	4	9	4	5	9	9	8	17

Fiber lengths

Fiber lengths were not run on these samples.

[a]See the Fiber Analysis procedure to gain a full understanding of this and the following table. Basically they provide a breakdown by weight percent of the fibrous and filamentous algae components of the sludge.

TABLE XVI

FIBER ANALYSIS OF SAMPLES FROM FIVE SELECTED
LOWER FOX RIVER SLUDGE BEDS
JULY 1971

Identification	Counts Field 1	Counts Field 2	Total Count	Weight Factor	Refined Count	Weighted Percentage
		Sample B 1-3				
Softwood unbleached sulfite	11	16	27	0.9	24	43
Softwood bleached sulfite	2	3	5	0.9	5	9
Softwood bleached kraft	5	8	13	0.9	12	21
Hardwood bleached sulfite	9	4	13	0.6	8	14
Groundwood	2	2	4	1.3	5	9
Filamentous algae	41	55	96	0.02	2	4
		Sample B 6-3				
Groundwood	17	21	38	1.3	49	96
Softwood bleached sulfite	--	1	1	0.9	1	2
Hardwood bleached sulfite	--	1	1	0.6	1	2
Filamentous algae	4	10	14	0.02	0.3	Trace
		Sample B 14-3				
Groundwood	30	33	63	1.3	82	95
Filamentous algae	121	84	205	0.02	4	5
		Sample B 22-3				
Groundwood	6	13	19	1.3	25	96
Filamentous algae	17	17	34	0.02	1	4
		Sample B 24-3				
Groundwood	27	22	49	1.3	64	96
Filamentous algae	69	61	130	0.02	3	4

TABLE XVII

COMPARISON OF RIVER SURVEY LABORATORY DATA

Bed	Date	Fiber, % ±0.2[a]	Volatile Solids / Fixed Solids ±0.005[a]	Volatile Solids, g. ±0.005[a]	Interstitial Water pH ±0.1[a]
B 1	June 1970	12.9	0.495	0.282	5.9
	Nov. 1970	12.4	0.363	0.826	6.6
	July 1971	18.1	0.696	1.061	6.4
B 6	June 1970	22.6	0.427	1.010	6.3
	Nov. 1970	26.8	0.949	0.298	6.9
	July 1971	7.1	0.271	1.617	6.5
B 14	June 1970	22.5	0.363	1.298	6.6
	Nov. 1970	--	--	--	--
	July 1971	20.4	0.612	1.007	6.4
B 22	June 1970	20.0	0.325	0.310	6.3
	Nov. 1970	17.3	0.298	1.782	7.3
	July 1971	9.8	0.193	1.357	6.9
B 24	June 1970	5.0	0.328	0.313	6.4
	Nov. 1970	6.5	0.307	1.282	6.8
	July 1971	6.1	0.321	1.135	6.8

[a]Standard deviation.

weight*. This definition is the basis for the beds shown in Fig. 16. Likely sites of sludge beds were indicated by gas evolution.

Also indicated on Fig. 16 are the sites of five sludge beds, designated B 1, B 6, B 14, B 22, and B 24. They were chosen as representative beds to avoid the immense task of analyzing in detail the massive number of sludge samples taken during the field surveys. The choice of locations was made so the whole length of the river was represented.

*A search of the available literature provided no definition of a fibrous sludge bed. An arbitrary definition for a sludge deposit was devised based on the experience gained in these river surveys.

Table XI summarizes the temperature, sludge depth, dissolved oxygen, and pH data of the June, 1970 river survey. These parameters are found to vary with bed location, but no trends or patterns are evident. All sludge depths were at least six inches; often the depth was greater than five feet, the maximum depth that could be measured with the probe used.

Table XII gives the levels of glucose found in the water over the top of the bed and the bed interstitial water for the five selected beds. There appears to be more glucose present in the bed interstitial water than in the river water, which is consistent with the supposition that anaerobic decomposition is occurring in the sludge bed. Table XIII summarizes the thioglycolate bacteria counts for the five selected bed locations. The data show that the farther downstream the bed the lower the bacteria count, but the significance of this is uncertain. Table XIV gives the nutrient levels found in the five selected beds and shows the variations which exist in these parameters. No correlations or consistent trends are evident in these data.

Tables XV and XVI give the fiber composition of the beds found in the June, 1970 and July, 1971 surveys. An analysis was not performed for the November, 1970 survey. Slides prepared for the June, 1970 survey did not contain enough fiber for an accurate analysis. The set of slides for the July, 1971 survey contained sufficient fiber, and the June, 1970 results are qualitatively the same.

It might be expected that the fiber found in a bed below a given mill would be representative of that mill's furnish. If there is appreciable scour and redistribution taking place, then other types of fiber would also be present and a noncharacteristic blend would be found. From the tables, it appears that all the beds, with the exception of those in Little Lake Butte des Morts, contain groundwood or chemigroundwood as the principal fiber component. This suggests (1) that beds are composites of fibers from several mills and not just composed of fibers from the mill directly upstream from the bed, and (2) that the chemical pulp fiber added to the river dissipates more rapidly than does the groundwood fiber. If this latter were not the case, more chemical fibers should have been present in the beds than were found. The bed which best illustrates these points is B 14, which is located directly below a kraft mill, yet its principal fiber component is groundwood. Traces of kraft pulp were present in the bed but not in significant amounts.

Table XVII is a comparison of several of the parameters which were monitored in each river survey. The percent fiber in the beds was generally higher than the 5% criterion; the range found was from 5 to 26.8% fiber. This table indicates that the bed properties do change between visits to the same river location, but no consistent trends are evident in the data. The monthly monitoring program which is discussed below amplifies the variability of bed parameters. This variability can be rationalized in terms of scour and additional deposition.

SLUDGE DISTRIBUTION MODEL

A significant result of the river surveys was to establish the sludge distribution in the Lower Fox River. In order to put the data in context, a mathematical model for predicting sludge distribution was developed. A complete discussion of the model together with all associated computer output is given in Appendix II.

In brief, the river was divided into 45 sections, and a volume average velocity was computed for each section under various conditions of flow and compared with two criteria for scour. The model criteria used to predict conditions suitable for deposition or scour were flow velocities of 1 or 2 ft./sec., with the first probably the more realistic. These seemed reasonable limits to choose based on the literature data for the scouring of sewage sludge deposits and mineral deposits (68, 69). Table XVIII defines the river sections which were used (from 20).

Bar graphs depicting the model predictions for 1969, 1970, and 1971, using the 1 ft./sec. criterion, are given in Fig. 17, 18, and 19. The model was applied to the maximum, minimum, and average flow conditions for each year as well as to the monthly average flow conditions. The sludge distribution model predicts that the river was probably scoured free of sludge in 1969 but not in 1970 or 1971. In 1970 and 1971 permanent bed locations were predicted in Little Lake Butte des Morts and in the lower portion of the river near Green Bay. The model predicted that three areas of the river remained free of sludge during these three years, Sections 4-5, Section 14, and Section 22. The remainder of the river had transient deposition of sludge. The portion of the river experiencing transient deposits was approximately 4/5 of the total river bottom.

The results of the June, 1970 river survey (Fig. 16, p. 47) are given in bar graph form on Fig. 15. It does not compare well at all with the predicted sludge distribution for the June average flow, but it is very similar to that for May. This is reasonable because the river survey was conducted just at the onset of the period of high flow in June, and the beds were in the process of being scoured but had not yet totally disappeared. The discrepancies between the model prediction for May and the finding of the survey can be rationalized in terms of the partial completion of scour. When the model predicted sludge in a section, that section was not always totally covered with sludge but usually contained sludge in the portions of slower flow in the section. This is to be expected since the model does not account for the true hydrodynamic flow pattern of the river. The model

TABLE XVIII

SUMMARY OF MODEL SECTIONS — LOWER FOX RIVER, WISCONSIN
(From 20)

Section Number	River Mile Points[a]	Approximate Location
1	38.63-38.1	Neenah Dam-Bergstrom Paper Co.
2	38.1 -37.62	Bergstrom Paper Co.-Kimberly-Clark Corp., Lakeview
3	37.62-37.24	K-C Lakeview-James Island
4	38.18-37.92	Menasha Dam-John Strange Paper Co.
5	37.92-37.24	John Strange Paper Co.-James Island
6	37.24-36.83	James Island-Menasha Lock
7	36.83-36.0	Menasha Lock-Ninth St., Menasha
8	36.0 -34.8	Ninth St., Menasha-Stroebe Island
9	34.8 -34.3	Stroebe Island-Mud Creek
10	34.3 -33.96	Mud Creek-Grignon Rapids Channel
11	33.96-32.1	Grignon Rapids Channel-Dam, Wisconsin-Michigan Power Co.
12	32.1 -31.65	Dam, WMPCO-Dam, Fox River Paper Co.
13	31.65-30.8	Dam, Fox River Paper Co.-Dam, Foremost Dairies, Inc.
14	30.8 -30.56	Dam, Foremost Dairies, Inc.-Consolidated Papers, Inc.
15	30.56-29.73	Consolidated Papers, Inc.-Appleton Sewage Treatment Plant
16	29.73-27.24	Appleton Sewage Treatment Plant-Dam, Kimberly-Clark Corp., Kimberly
17	27.24-26.8	Dam, K-C, Kimberly-Jefferson St., Little Chute
18	26.8 -26.4	Jefferson St., Little Chute-Dam, Guard Lock, Little Chute
19	26.4 -25.6	Dam, Guard Lock, Little Chute-Dam, Combined Locks Paper Co.
20	25.6 -25.1	Dam, Combined Locks Paper Co.-Sanatorium Road, Little Chute

[a]See end of table for footnote.

TABLE XVIII (Continued)

SUMMARY OF MODEL SECTIONS — LOWER FOX RIVER, WISCONSIN
(From 20)

Section Number	River Mile Point[a]	Approximate Location
21	25.1 -23.93	Sanatorium Road-Dam, LaFollette Park, Kaukauna
22	23.93-23.2	Dam, LaFollette Park, Kaukauna-Thilmany Pulp & Paper Co.
23	23.2 -22.5	Dam, Thilmany Pulp & Paper Co.-Downstream of Thilmany Pulp & Paper Co.
24	22.5 -21.0	Downstream of Thilmany Pulp & Paper Co.
25	21.0 -19.18	Upstream of Kaukauna Electric & Water Dept.
26	19.18-17.4	Kaukauna Electric & Water Dept.-Plum Creek
27	17.4 -15.0	Plum Creek-Apple Creek
28	15.0 -13.1	Apple Creek-Dam, Charmin Paper Products Co.
29	13.1 -12.6	Dam, Charmin Paper Products Co.-Lost Dauphin State Park, Little Rapids
30	12.6 -12.1	Lost Dauphin State Park, Little Rapids-Hickory Grove Sanatorium
31	12.1 -10.4	Hickory Grove Sanatorium-Old Plank Road, DePere
32	10.4 - 7.3	Old Plank Road, DePere-Dam, DePere
33	7.3 - 6.97	Dam, DePere-U.S. Paper Mills Corp.
34	6.97- 6.25	U.S. Paper Mills Corp.-Sewage Disposal Plant, DePere
35	6.25- 5.7	Sewage Disposal Plant, DePere-Ashwaubenon Creek
36	5.7 - 4.8	Ashwaubenon Creek-Dutchman Creek
37	4.8 - 4.0	Dutchman Creek-Reimers Meat Products, Inc.
38	4.0 - 3.7	Reimers Meat Products, Inc.-Fort Howard Paper Co.
39	3.7 - 2.63	Fort Howard Paper Co.-Porlier St., Green Bay
40	2.63- 1.3	Porlier St., Green Bay-East River

[a]See end of table for footnote.

TABLE XVIII (Continued)

SUMMARY OF MODEL SECTIONS — LOWER FOX RIVER, WISCONSIN
(From 20)

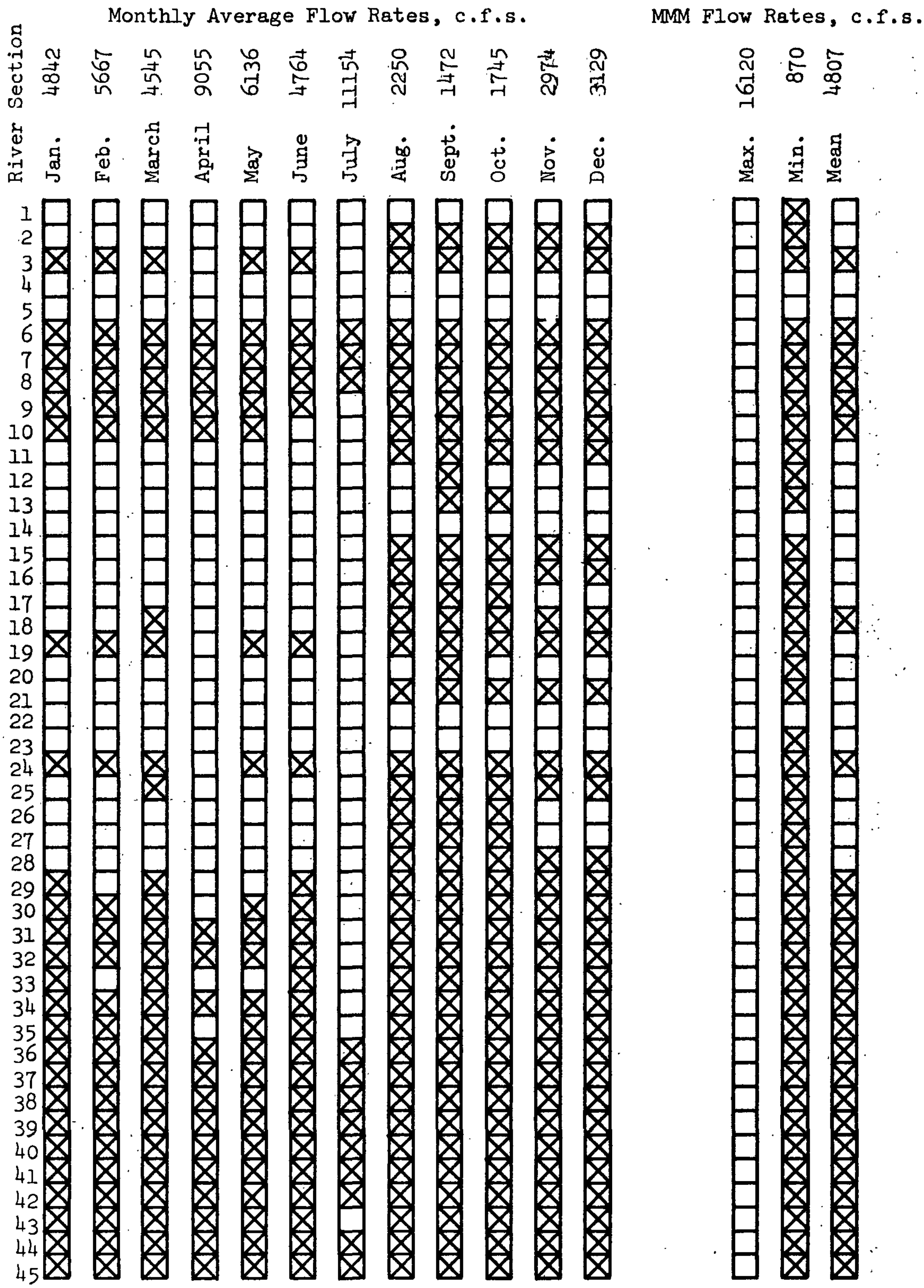
Section Number	River Mile Point[a]	Approximate Location
41	1.3 -1.0	East River-Charmin Paper Products Co.
42	1.0 -0.7	Charmin Paper Products Co.-Green Bay Packaging, Inc.
43	0.7 -0.33	Green Bay Packaging, Inc.-The C. Reiss Coal Co.
44	0.33-0.14	The C. Reiss Coal Co.-Green Bay Yacht Club
45	0.14-0.00	Green Bay Yacht Club-McDonald Lumber Co.

[a]Mile points initiate at the river mouth in Green Bay.

also does not compensate in any way for the time which would be required to physically scour a deposit. Further refinement of the model is an area of suggested further work. Considering the simplicity of the model, it does a surprisingly good job of predicting the sludge distribution in the Lower Fox River. The model predictions fit well with the impressions gained in the field surveys and monthly monitoring program with regard to the variations observed in the parameters monitored, in that no definite patterns are evident in the parameters monitored nor is there a definite pattern to the transient nature of the sludge deposit.

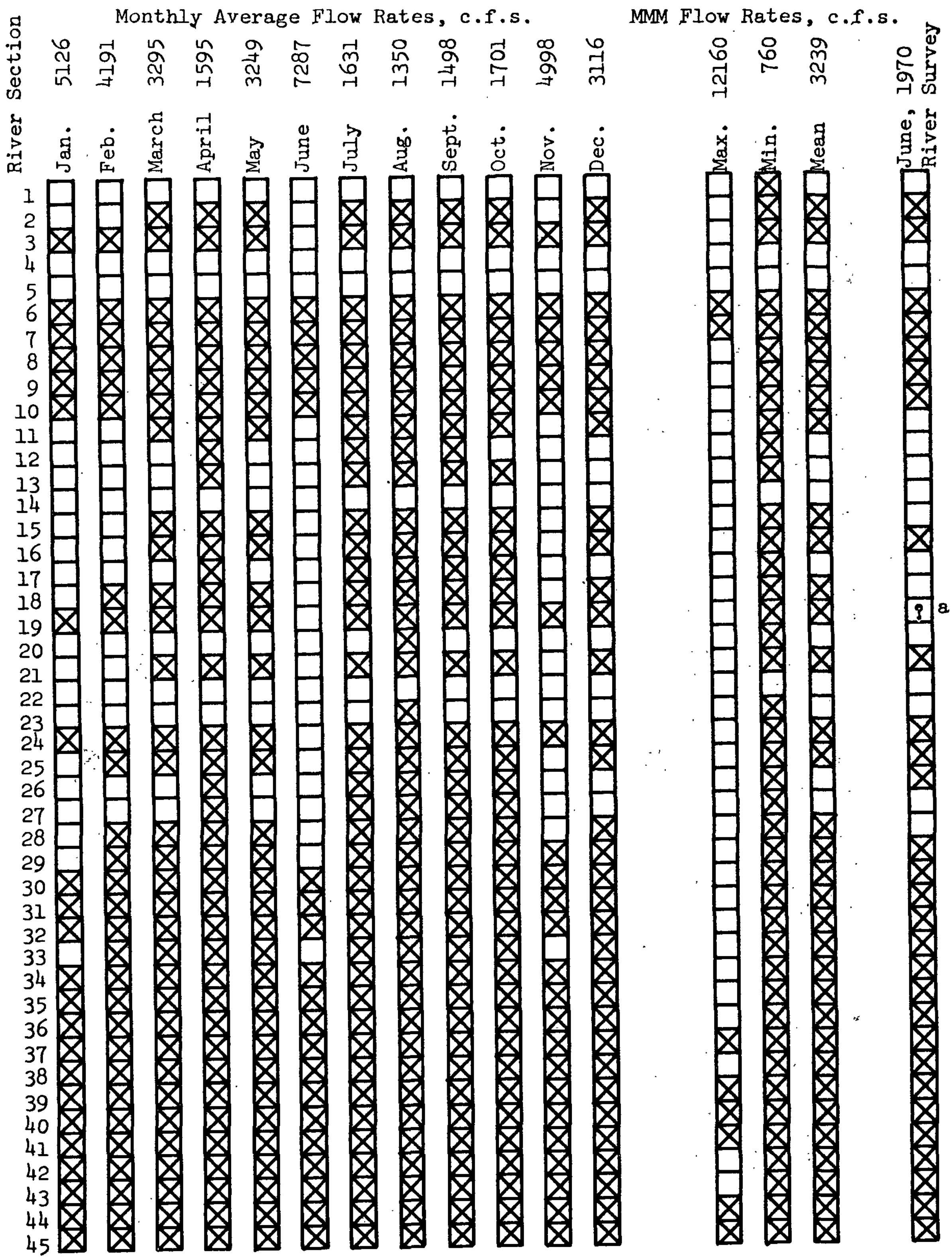
MONTHLY MONITORING PROGRAM

The purpose of the monthly monitoring program was to observe changes which took place at a single bed site over a yearly cycle. The bed selected for monthly monitoring was located downstream from Combined Locks and is designated B 6 on Fig. 16, p. 47. The data from this program are presented in Tables XIX through XXV and Fig. 20. In addition to these data, 35-mm. slides of sludge core samples



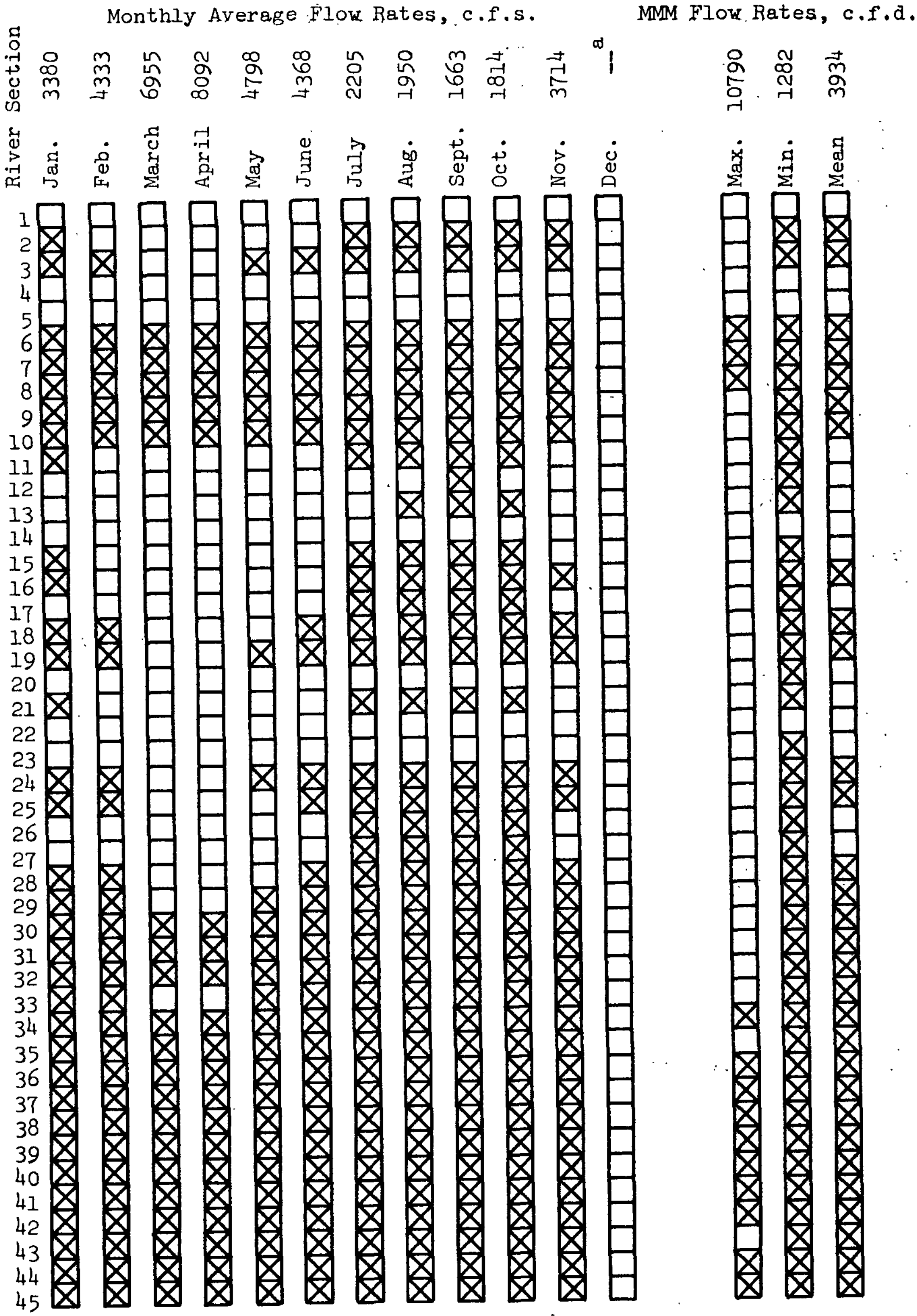
Key: ☒ Indicates Sludge Predicted to be in Section ☐ Indicates no Sludge Predicted to be Present

Figure 17. Model Predictions for 1969 (1 Ft./Sec. Flow Criterion)



[a]This section was not surveyed because access to it by boat was not possible.

Figure 18. Model Predictions for 1970 and Comparison with River Survey Results (1 Ft./Sec. Flow Criterion)



[a]Flow rate data not available for December, since calculations were performed in November, 1971.

Figure 19. Model Predictions for 1971 (1 Ft./Sec. Flow Criterion)

TABLE XIX

SUMMARY OF MONTHLY SAMPLING DATA
SLUDGE BED B 6

Sludge sample Date of visit	SI 17 Nov. 69	SIII 23 Feb. 70	SIV 31 March 70	SV 23 April 70	SVII 29 May 70
Ambient temp., °C. ±0.5[a]	10	2	5.5	16	21.3
Water temp., °C. ±0.5	5	3	7	11.8	20.3
Av. sludge temp., °C. ±0.5	9	5	7	11.1	18.2
Sludge pH ±0.1	5.1	4.8	5.0	5.7	5.9
Water pH ±0.1	7.5	6.3	7.7	6.8	6.5
Dissolved oxygen in water, p.p.m. ±0.1	11.0	11.2	11.3	5.1	7.8
Sludge depth ±2"	1'8"	1'3"	2'8"	3'0"	3'6"
Water depth ±2"	5'5"	5'6"	4'7"	3'6"	3'6"
Gas evolution	Yes	No	No	Slightly	Slow
VS/FS ±0.005	2.03	2.86	2.88	2.71	1.13
TS/FS ±0.005	3.04	3.78	3.87	3.68	2.12
Fixed solids, g. ±0.003	0.346	0.291	0.281	0.344	0.404
% Fiber ±0.2					
Bacteria/ml. ±10%					
Glucose, g./l. ±0.003[b]					
Acids, g./l. ±0.02[b]					
Acetic					
Propionic					
Butyric					

See end of table for footnotes.

TABLE XIX (Continued)

SUMMARY OF MONTHLY SAMPLING DATA
SLUDGE BED B 6

Sludge sample Date of visit	SVII 16 June 70	SVIII 28 July 70	SIX 31 Aug. 70	SX 21 Sept. 70	SXI 26 Oct. 70
Ambient temp., °C. ±0.5[a]	28.8	38.9	30.3	19.7	13.0
Water temp., °C. ±0.5	24.2	30.1	24.2	21.1	13.2
Av. sludge temp., °C. ±0.5	20.0	25.3	22.4	19.6	13.9
Sludge pH ±0.1	6.3	6.1	6.2	6.3	5.8
Water pH ±0.1	8.7	6.7	7.2	6.9	7.3
Dissolved oxygen in water, p.p.m. ±0.1	6.2	2.2	2.3	0.7	6.3
Sludge depth ±2"	3'0"	2'9"	2'0"	3'0"	3'0"
Water depth ±2"	3'6"	4'0"	4'6"	3'6"	4'0"
Gas evolution	Yes	Slow	Slow	Yes	Yes
VS/FS ±0.005	0.427	0.508	0.656	0.394	0.949
TS/FS ±0.005	1.43	1.51	1.66	1.48	1.95
Fixed solids, g. ±0.003	2.370	1.316	1.092	1.892	0.495
% Fiber ±0.2	22.6		18.1	14.7	26.7
Bacteria/ml. ±10%	1.13×10^6		1.7×10^6	2.75×10^6	2.78×10^5
Glucose, g./l. ±0.003[b]	0.005		0.003	0.002	
Acids, g./l. ±0.02[b]					
Acetic	Trace		0.012	0.00	0.20
Propionic	Trace		0.012	0.00	0.21
Butyric	Trace		Trace	0.00	0.03

See end of table for footnotes.

TABLE XIX (Continued)

SUMMARY OF MONTHLY SAMPLING DATA
SLUDGE BED B 6

Sludge sample Date of visit	SXII 30 Nov. 70	SXIII 28 Jan. 71	SXIV 2 March 71	SXV 29 March 71
Ambient temp., °C. ±0.5[a]	4.0	-1.0	2.6	8.6
Water temp., °C. ±0.5	2.2	0.0	2.6	5.4
Av. sludge temp., °C. ±0.5	3.6	1.5	3.5	7.5
Sludge pH ±0.1	6.9	6.6	6.45	6.8
Water pH ±0.1	7.8	7.4	7.8	7.7
Dissolved oxygen in water, p.p.m. ±0.1	13.2	13.4	12.8	11.8
Sludge depth ±2"	2'10"	3'3"	4'3"	3'6"
Water depth ±2"	3'6"	3'0"	3'2"	3'6"
Gas evolution	Slightly	No	No	No
VS/FS ±0.005	0.949	0.925	1.20	0.714
TS/FS ±0.005	1.95	1.92	1.84	1.74
Fixed solids, g. ±0.003	0.315	0.458	0.416	0.892
% Fiber ±0.2	32.7	21.1	35.0	29.9
Bacteria/ml. ±10%	1.3×10^6	7.02×10^5	2.4×10^6	5.24×10^5
Glucose, g./l. ±0.003[b]	0.001	0.003	0.003	0.004
Acids, g./l. ±0.02[b]				
Acetic	0.15	0.26	0.22	0.07
Propionic	0.12	0.21	0.23	0.05
Butyric	0.02	0.02	0.04	0.00

See end of table for footnotes.

TABLE XIX (Continued)

SUMMARY OF MONTHLY SAMPLING DATA
SLUDGE BED B 6

Sludge sample Date of visit	SXVI 29 April 71	SXVII 26 May 71	SXVIII 30 June 71	SXIX 14 July 71	SXX 7 Sept. 71
Ambient temp., °C. ±0.5[a]	13.0	13.0	25.9	32.4	38.7
Water temp., °C. ±0.5	10.2	14.6	27.7	24.9	25.2
Av. sludge temp., °C. ±0.5	9.5	13.2	23.2	23.9	23.4
Sludge pH ±0.1	6.4	6.0	6.2	6.5	6.1
Water pH ±0.1	8.1	6.7	7.4	8.1	7.2
Dissolved oxygen in water, p.p.m. ±0.1	12.4	6.4	2.2	0.2	4.4
Sludge depth ±2"	3'0"	3'9"	3'8"	3'4"	3'6"
Water depth ±2"	3'10"	2'6"	3'5"	3'8"	3'0"
Gas evolution	Slightly	Slow	Yes	Yes	Yes
VS/FS ±0.005	0.482	0.470	0.329	0.271	0.230
TS/FS ±0.005	1.47	1.47	1.43	1.27	1.23
Fixed solids, g. ±0.003	1.426	1.996	3.784	5.968	5.872
% Fiber ±0.2	32.6	18.7	12.8	7.1	11.2
Bacteria/ml. ±10%	6.07×10^5	1.33×10^6	9.18×10^6		4.28×10^6
Glucose, g./l. ±0.003[b]	0.009	0.008	0.008	0.014	0.016
Acids, g./l. ±0.02[b]					
Acetic	0.09	0.11	0.00	0.00	0.00
Propionic	0.00	0.00	0.00	0.00	0.00
Butyric	0.00	0.00	0.00	0.00	0.00

[a]All ranges are standard deviations unless otherwise specified.

[b]95% Confidence limits.

TABLE XX

FIBER LENGTH

Date	Sample	Weighted Average, mm. ±0.04[a]	Arithmetic Average, mm. ±0.03[a]
31 March 70	SIV	0.93	0.63
23 April 70	SV	0.87	0.65
29 May 70	SVI	0.80	0.56
16 June 70	SVII	--	--
28 July 70	SVIII	0.75	0.58
31 Aug. 70	SIX	0.81	0.61
21 Sept. 70	SX	0.72	0.58
26 Oct. 70	SXI	0.99	0.79
30 Nov. 70	SXII	0.98	0.67
28 Jan. 71	SXIII	0.98	0.73
2 March 71	SXIV	1.15	0.83
29 March 71	SXV	1.03	0.74
29 April 71	SXVI	0.89	0.70
26 May 71	SXVII	0.84	0.59
14 July 71	SXIX	--	--
7 Sept. 71	SXX	0.67	0.49

[a]Standard deviation.

TABLE XXI

FIBER COMPOSITION OF BED B 6

Date	Sample	Hardwood Kraft, % ±3[a]	Softwood Chemical, % ±3[a]	Cold Soda or Chemigroundwood, % ±4[a]
31 March 70	SIV	6	14	78
23 April 70	SV	11	17	72
29 May 70	SVI	5	14	81
16 June 70	SVII	--	--	--
28 July 70	SVIII	3	5	91
31 Aug. 70	SIX	2	14	82
21 Sept. 70	SX	4	8	88
26 Oct. 70	SXI	3	7	88
30 Nov. 70	SXII	0	2	96
28 Jan. 71	SXIII	1	3	95
2 March 71	SXIV	5	15	76
29 March 71	SXV	4	13	81
29 April 71	SXVI	2	5	92
26 May 71	SXVII	3	8	86
7 Sept. 71	SXX	Trace	3	90

[a]Standard deviation.

TABLE XXII

NITROGEN AND PHOSPHORUS CONTENT OF MONTHLY SAMPLES FROM B 6

Date	Sample	Ammonia, mg./l. ±0.05[a]	NO_3, mg./l. ±0.1[a]	NH_3+NO_3, mg./l.	NO_2, mg./l. ±0.03[a]	Organic N, mg./l. ±0.05[a]	PO_4, mg./l. ±0.02[a]
			A. Water Over Bed				
31 March 70	SIV	0.16	0.07	0.23	0.03	0.55	0.11
23 April 70	SV	0.11	0.12	0.23	0.02	2.04	0.04
29 May 70	SVI	0.20	0.22	0.42	0.04	2.33	0.01
16 June 70	SVII	0.62	0.32	0.94	0.02	0.13	0.01
28 July 70	SVIII	0.17	0.29	0.46	0.01	2.38	0.01
31 Aug. 70	SIX	1.20	0.23	1.43	0.01	0.01	0.11
21 Sept. 70	SX	2.00	0.023	2.02	0.003	2.82	0.01
26 Oct. 70	SXI	0.032	0.05	0.082	0.003	3.07	0.014
30 Nov. 70	SXII	0.06	0.04	0.10	0.005	1.48	0.01
28 Jan. 71	SXIII	0.35	0.08	0.43	0.005	0.35	0.06
2 March 71	SXIV	0.20	0.07	0.27	0.004	1.88	0.04
29 March 71	SXV	0.72	0.59	1.31	0.004	1.31	0.03
29 April 71	SXVI	0.18	0.29	0.47	0.003	3.30	0.01
26 May 71	SXVII	0.30	0.36	0.66	0.007	2.20	0.07
30 June 71	SXVIII	0.29	0.34	0.63	0.001	0.74	0.06
14 July 71	SXIX	0.16	4.22	4.38	0.010	1.07	0.04
7 Sept. 71	SXX	0.15	0.22	0.37	0.005	1.27	0.20
			B. Interstitial Water				
31 March 70	SIV	1.05	0.31	1.36	0.11	3.39	0.10
23 April 70	SV	0.26	0.24	0.50	0.05	6.12	0.10
29 May 70	SVI	0.28	0.23	0.51	0.01	10.7	0.02
16 June 70	SVII	2.77	0.98	3.76	--	0.34	0.58
28 July 70	SVIII	15.6	0.30	15.9	0.17	0.70	0.09
31 Aug. 70	SIX	7.40	0.25	7.65	0.06	1.66	0.23
21 Sept. 70	SX	4.84	0.061	4.90	0.007	1.35	0.008
26 Oct. 70	SXI	1.39	0.933	2.32	0.004	2.64	0.005
30 Nov. 70	SXII	1.80	0.11	1.91	0.03	1.73	0.030
28 Jan. 71	SXIII	2.22	0.15	2.37	0.007	2.81	0.04
2 March 71	SXIV	3.76	0.28	4.04	0.006	5.11	0.01
29 March 71	SXV	2.10	0.26	2.36	0.004	0.84	0.07
29 April 71	SXVI	0.46	0.22	0.68	0.023	2.34	0.04

See end of table for footnotes.

TABLE XXII (Continued)

NITROGEN AND PHOSPHORUS CONTENT OF MONTHLY SAMPLES FROM B 6

Date	Sample	Ammonia, mg./l. ±0.05[a]	NO_3, mg./l. ±0.1[a]	NH_3+NO_3, mg./l.	NO_2, mg./l. ±0.03[a]	Organic N, mg./l. ±0.05[a]	PO_4, mg./l. ±0.02[a]
26 May 71	SXVII	5.79	0.34	6.13	0.010	7.86	0.02
30 June 71	SXVIII	0.30	0.35	0.65	0.002	1.63	0.18
14 July 71	SXIX	0.92	0.26	1.18	0.005	1.02	0.18
7 Sept. 71	SXX	0.07	9.67	9.74	11.47	1.34	0.28

C. Sludge

Date	Sample	Ammonia,[b] % ±0.01[a]	Organic N,[b] % ±0.01[a]
31 March 70	SIV	0.01	0.33
23 April 70	SV	0.01	0.71
29 May 70	SVI	0.02	0.78
16 June 70	SVII	0.01	0.50
28 July 70	SVIII	0.008	0.47
31 Aug. 70	SIX	0.03	0.70
21 Sept. 70	SX	0.003	0.51
26 Oct. 70	SXI	0.01	0.53
30 Nov. 70	SXII	0.06	0.55
28 Jan. 71	SXIII	0.01	0.66
2 March 71	SXIV	<0.005	0.58
29 March 71	SXV	0.18	0.43
29 April 71	SXVI	0.01	0.58
26 May 71	SXVII	0.02	0.51
30 June 71	SXVIII	0.02	0.26
14 July 71	SXIX	0.01	0.19
7 Sept. 71	SXX	0.00	0.20

[a]Standard deviation.

[b]As percent of total solids.

TABLE XXIII

PHOSPHORUS CONTENT OF MONTHLY SLUDGE SAMPLES FROM BED B 6

Date	Sample	Phosphorus as % Ovendry Solids ±0.1	Volatile Solids as % Ovendry Solids ±0.1[a]	$\frac{mg.\ P}{g.\ VS} = \frac{\%\ P \times 10^3}{\%\ VS}$ ±1[a]
23 Feb. 70	SIII	0.7	75.6	9.0
23 April 70	SV	0.4	73.5	6.1
16 June 70	SVII	0.6	30.0	18.3
28 July 70	SVIII	0.5	33.6	15.2
31 Aug. 70	SIX	0.5	39.5	7.8
21 Sept. 70	SX	0.3	25.6	10.3
26 Oct. 70	SXI	0.5	51.2	8.8
30 Nov. 70	SXII	0.5	48.5	10.6
28 Jan. 71	SXIII	0.5	48.1	11.0
2 March 71	SXIV	0.4	53.2	7.1
29 March 71	SXV	0.5	41.8	11.7
29 April 71	SXVI	0.5	32.7	15.3
26 May 71	SXVII	0.5	32.0	15.6
30 June 71	SXVIII	0.5	22.9	21.0
14 July 71	SXIX	0.5	21.6	23.1
7 Sept. 71	SXX	0.5	19.1	26.1

[a]Standard deviation.

TABLE XXIV

ORGANIC NITROGEN CONTENT OF MONTHLY SLUDGE SAMPLES FROM BED B 6

Date	Sample	Nitrogen as % Ovendry Solids ±0.01[a]	Volatile Solids as % Ovendry Solids ±0.1[a]	$\frac{mg.\ N}{g.\ VS} = \frac{\%\ N \times 10^3}{\%\ VS}$ ±0.1[a]
23 April 70	SV	0.71	73.5	9.7
16 June 70	SVII	0.50	30.0	16.7
28 July 70	SVIII	0.47	33.6	14.0
31 Aug. 70	SIX	0.70	39.5	17.7
21 Sept. 70	SX	0.51	25.6	19.9
26 Oct. 70	SXI	0.53	51.2	10.4
30 Nov. 70	SXII	0.55	48.5	11.3
28 Jan. 71	SXIII	0.66	48.1	13.7
2 March 71	SXIV	0.58	53.2	11.0
29 April 71	SXVI	0.58	32.7	17.7
26 May 71	SXVII	0.51	32.0	15.9
30 June 71	SXVIII	0.26	22.9	11.3
14 July 71	SXIX	0.19	21.6	8.8
7 Sept. 71	SXX	0.20	19.1	10.5

[a]Standard deviation.

TABLE XXV

TRACE METAL CONCENTRATION OF THREE SLUDGE SAMPLES FROM BED B 6

	Sample SIII	Sample SV	Sample SIX
		All values ±3 to 5%[a]	
Total ovendry solids[b]	17.2	11.2	18.5
Ash (at 550°C.)[c]	10.6	3.98	3.84
Magnesium[c]	0.14	0.043	0.048
Calcium[c]	0.18	0.070	0.080
Iron[c]	0.22	0.080	0.066
Aluminum[c]	1.6	0.55	0.48
Silicon[c]	2.2	0.98	0.96
Lead[c]	0.0056	0.0016	0.0014
Zinc[c]	0.36	0.36	0.36
Sodium[c]	0.049	0.018	0.016
Titanium[c]	0.12	0.10	0.094
Copper[c]	0.0022	0.00083	0.0018
Manganese[c]	0.034	0.018	0.013
Potassium[c]	<0.5	<0.18	<0.17

[a]Standard deviation.

[b]As percent of total wet weight.

[c]As percent of ovendry solids.

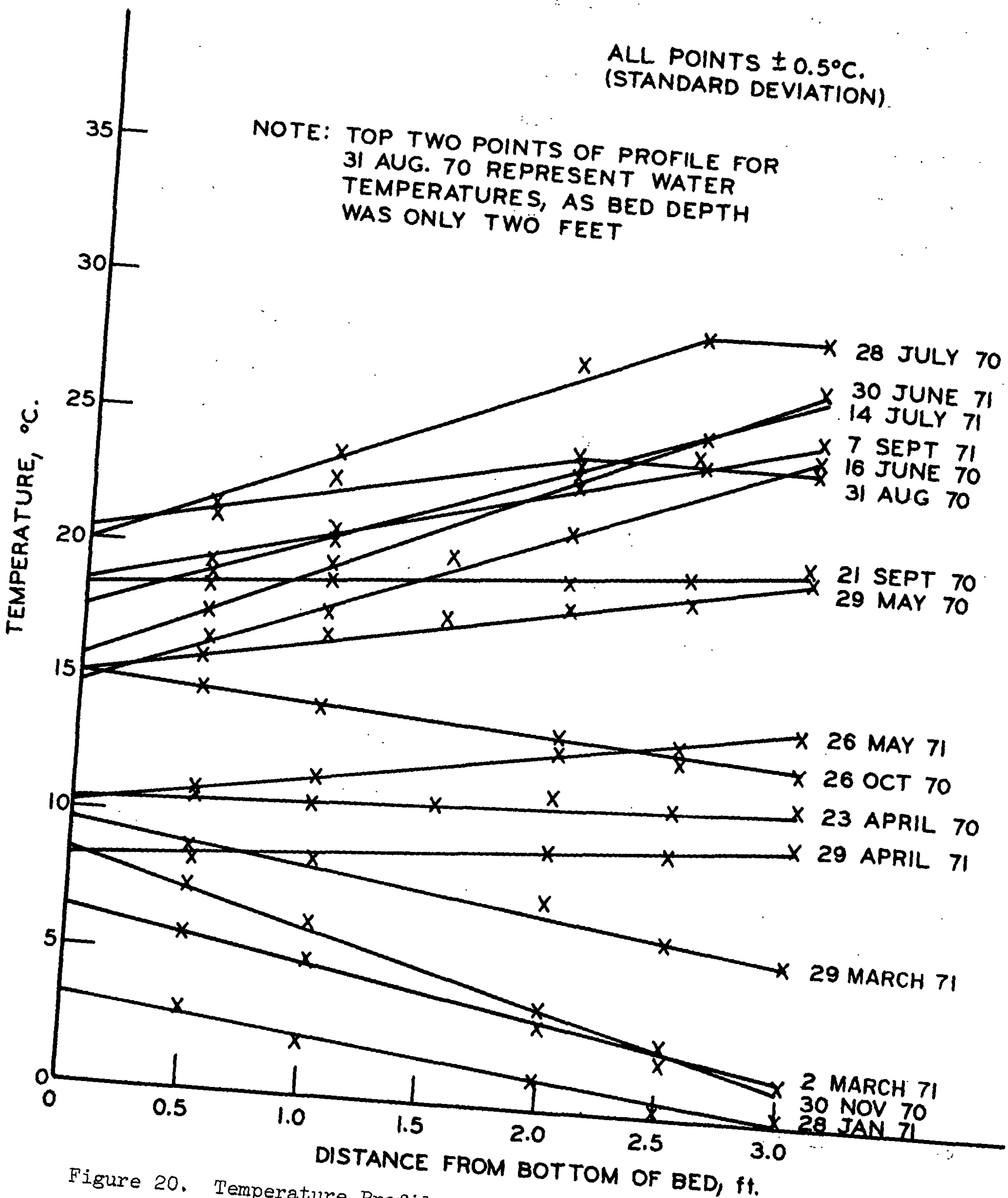


Figure 20. Temperature Profile in Bed B 6 at Time of Monthly Samplings

were taken on most monthly visits; these slides are on permanent file at The Institute of Paper Chemistry and are not included in this dissertation.

One of the trends noted during this study was the build-up of the fiber content of the bed over the winter months. This manifested itself in a higher ratio of volatile solids (VS) to fixed solids (FS), as can be seen in Table XIX. This build-up of fiber was also observed visually as a mottled appearance of the winter core samples.

Table XIX illustrates that the nature of the bed changed significantly during the period of observation commencing with the first visit in November, 1969. Several parameters were quite changed between the visits of November, 1969 to April, 1970 and those of the same period a year later, i.e., November, 1970 to April, 1971. Bed samples from the former visits had much greater fiber content than those from the latter period. The pH values of the samples from the former visits were in the vicinity of five, while those of the latter were around six.

Another difference found between the summer and the winter months was that the winter sludge samples contained measurable amounts of organic acids while the summer samples had none (see Table XIX). This may be because the methane bacteria are more sensitive to temperature than are the cellulose-decomposing bacteria. The low winter temperatures cause the rate of acid utilization to drop, and thus a higher acid concentration is built up.

Gas evolution from the bed occurred only during the warmer months of April to November, and floating sludge was present only from June to September, the most active decomposition period for sludge beds.

The qualitative picture of sludge behavior which emerges from the monthly monitoring program is that of fibrous solids build-up during the winter months, sludge scour and redistribution in the spring, an active period of decomposition during the summer and fall months, and then a return to the winter condition. The summer and early fall months are characterized by active gas evolution and floating sludge. As winter approaches the floating sludge disappears, and the gas evolution gradually lessens and finally ceases.

Tables XX and XXI give the fiber composition and fiber length data for all of the monthly samples. The lack of definite pattern in the results is typical of many of the parameters monitored and is probably due to the effects of material continuously being added to and removed from the bed. It was anticipated that these data would show a seasonal pattern, but none is evident. The continual addition and scour seem to override any trend which might otherwise be present.

The periods of active decomposition correspond to periods of high temperature. Figure 20 shows the temperature profile in the sludge bed at various times of the year. The temperature experienced by the sludge material ranges from 1 to 30°C.

The temperature profile through the bed is linear, having a positive slope during the warmer months and a negative slope during the colder months. The linearity of the profile indicates that the amount of heat generated by the decomposition process is negligible in comparison with that conducted through the bed from outside the bed. If there were significant heat generation in the bed a non-linear profile would result. (The broken line profile of 31 August, 1970 resulted because the bed depth was only two feet; therefore the top two points actually represent water temperature.)

Another important observation from the monthly monitoring program is the determination of the amounts of nitrogen and phosphorus present in the bed. Table XXII summarizes the results of these analyses. As was pointed out in the Literature Review, the amounts of nitrogen and phosphorus required to sustain decomposition are 2-60 mg. nitrogen and 1-10 mg. phosphorus per g. cellulose (p. 8; Table I, p. 9). The amounts of trace metal ions thought to be required are presented in Tables III and IV of the literature section (p. 10). Tables XXIII, XXIV, and XXV indicate that there probably are sufficient quantities of nitrogen, phosphorus, and trace metals present in the bed to sustain anaerobic fermentation. These analyses do not reveal whether the nutrients are present in a usable form but only that sufficient amounts are present.

LABORATORY STUDIES

INTRODUCTION

The river surveys and monthly monitoring program point out the importance of scour and flotation as mechanisms of removing sludge from a river location but shed very little light on the role of decomposition.

Two types of decomposition occur in fibrous sludge beds, aerobic and anaerobic. The aerobic zone comprises only the top 1 to 2 cm. of the bed (5, 6), the remainder being anaerobic. Aerobic rates of decomposition are higher than anaerobic rates; but since such a small fraction of the bed is aerobic, anaerobic processes would be expected to dominate the decomposition. If bed life is calculated on the assumption that the bed destruction is due entirely to the aerobic decomposition that occurs, a life of 300 to 400 years is predicted (see Appendix III). Thus, the laboratory program dealt only with anaerobic decomposition.

The qualitative model of anaerobic decomposition, shown in Fig. 5 of the literature section (p. 18), served as the basis for planning the laboratory program. The goal of the laboratory program was to answer several questions suggested by the model: (1) Does this process actually occur in a fibrous sludge bed; (2) If it does occur, what is the rate-limiting step in the sequence; (3) Assuming it occurs, is the process limited by lack of nutrients; (4) How does temperature affect the decomposition process; and (5) What mass transfer considerations are important?

In conducting these studies the question of sample variability became evident and led to studies of variation in the rate of decomposition of sludge with large changes in river position and time of the year. The question of sample variability at a bed site was explored by sampling at nine points on a 40-yard square (⋮⋮⋮); the variability was found to be insignificant.

DEMONSTRATION OF ANAEROBIC DECOMPOSITION OF CELLULOSE

The question concerning the existence of anaerobic decomposition of cellulose in the river system was illuminated by the following observations. Laboratory analysis revealed the presence of glucose and acetic acid in sludge interstitial water and carbon dioxide and methane in the gas evolved. Thus, the required physical manifestations of the process are present. Figure 21 shows photomicrographs of fibers from a sludge bed which are in a degraded, eroded state, perhaps indicating that bacterial decomposition of the fiber is taking place in the bed. These photomicrographs look similar to those shown by Siu (1) in which bacterial degradation was occurring.

Two procedures were used in the laboratory to demonstrate the existence of anaerobic decomposition of cellulose. First, a model sludge system was constructed with a high cellulose content pulp (kraft pulp) as the only carbon source (see Appendix IV for composition of model sludge). When inoculated with sludge taken from the river it slowly produced carbon dioxide and methane. An identical control which lacked only the kraft pulp was similarly inoculated and produced no gas. Therefore, the sludge contained the bacteria necessary to anaerobically decompose cellulose.

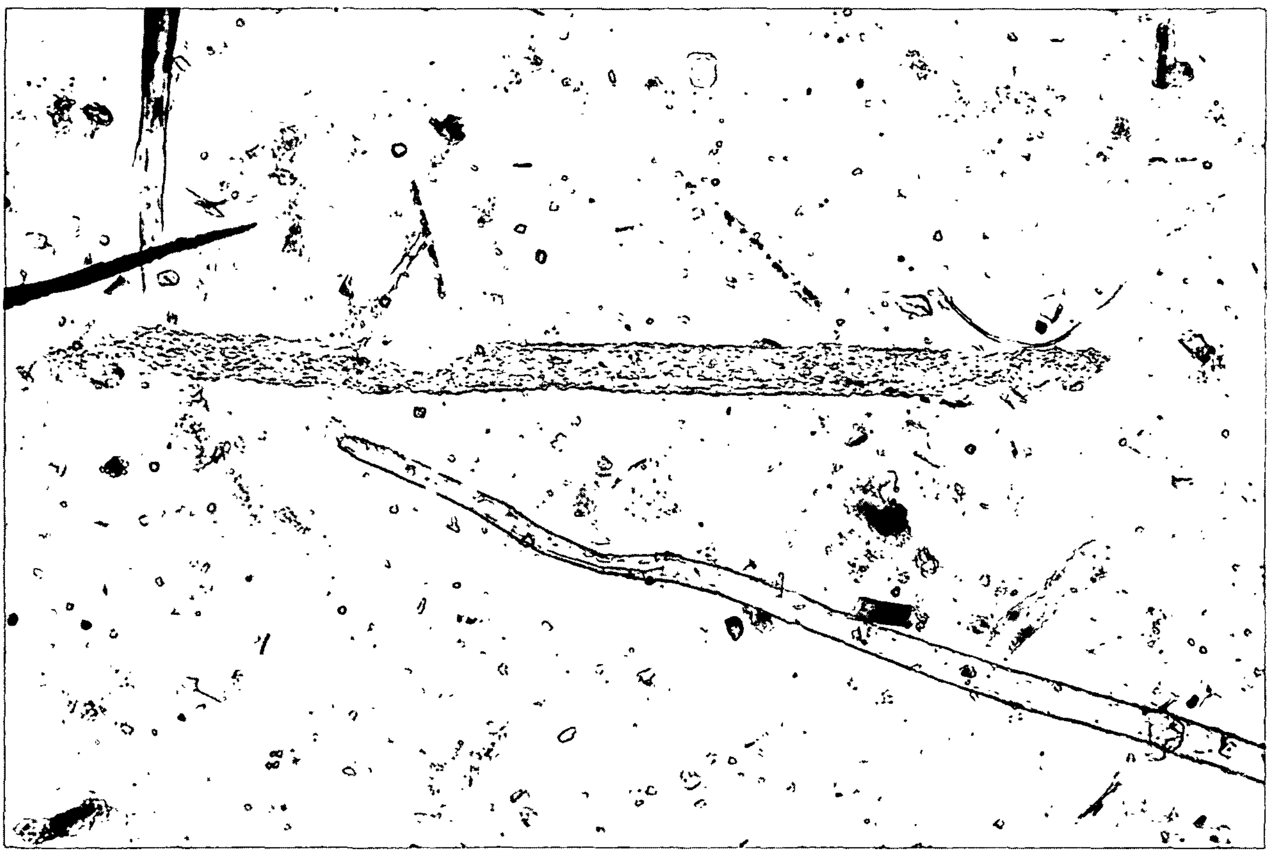


Figure 21. Softwood Chemical Fibers. 185 X.
Partially Decomposed and Relatively
Unattacked

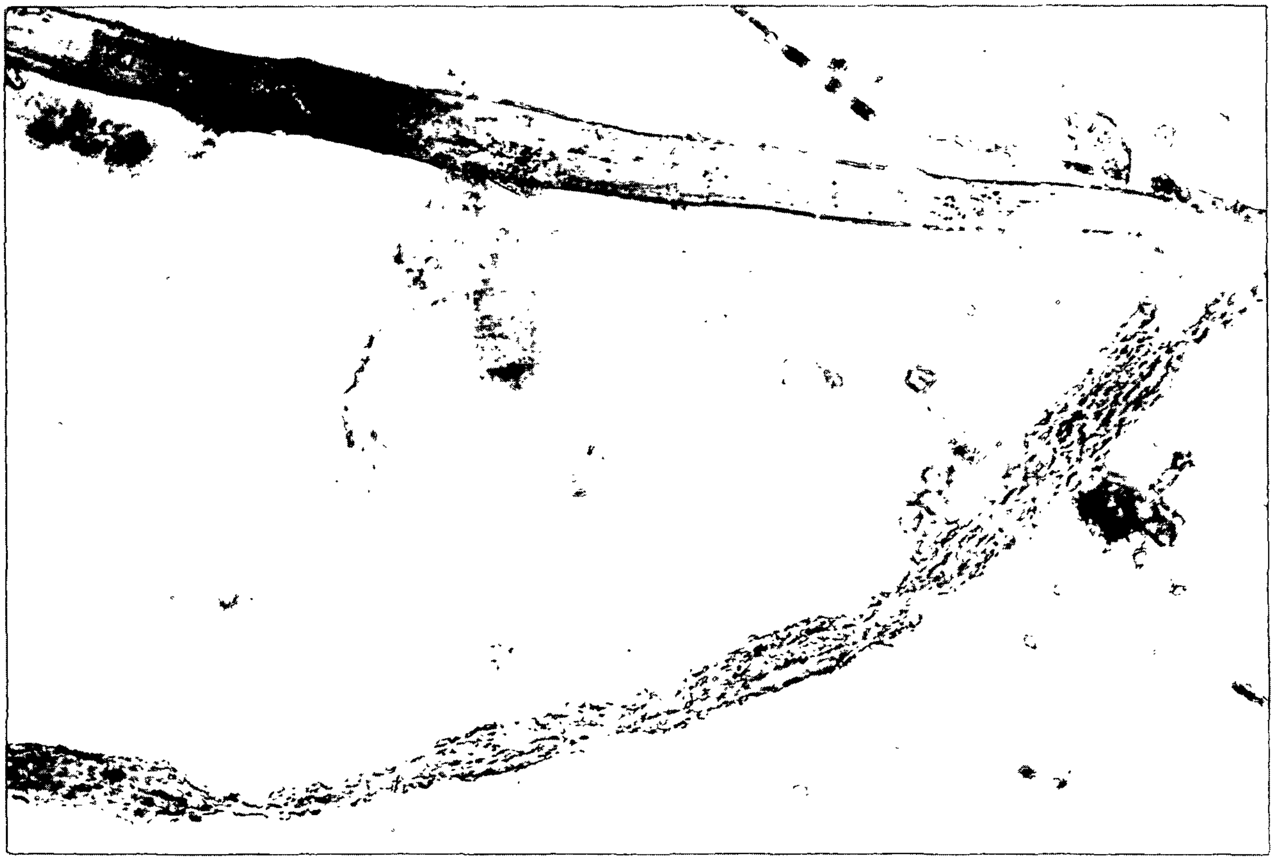


Figure 21 (Cont'd). Hardwood Chemical Groundwood Fibers. 185 X. Relatively Unattacked and in a Late Stage of Decomposition

Additional evidence that anaerobic decomposition of fiber is taking place in the river system was gained by the addition of ^{14}C-labelled cellulose to sludge and the detection of $^{14}CO_2$. This experiment was performed in the following manner: To six vessels on the Warburg apparatus were added 50 ml. of sludge SXIII. To two of the flasks were added 0.18 g. of ^{14}C-labelled aspen kraft pulp dispersed in 20 ml. of water; to two were added 0.18 g. of ^{14}C-labelled simulated groundwood (prepared by beating pieces of ^{14}C-labelled aspen twigs in a Waring Blendor for 30 min. at 1% concentration); and to the last two were added only 20 ml. of water to act as controls. All vessels were purged with nitrogen, sealed, and placed in the water bath at 25°C.; they were not agitated. Gas produced was monitored every 36 hr. for composition and radioactivity. The initial activity of the kraft pulp added to the sludge was 2.35 mc./g., and that of the simulated groundwood was 7.3 mc./g.

The results of this study are summarized in Fig. 22 and 23 and Table XXVI. Figure 22 illustrates that the gas produced by the anaerobic decomposition process contained $^{14}CO_2$ in the initial sample from both the kraft pulp and the simulated groundwood vessels and that increasing amounts of $^{14}CO_2$ were produced during each subsequent 36-hour monitoring period. If these individual sample activity data are converted into the total amount of $^{14}CO_2$ produced, a mass balance on the radioactive ^{14}C can be made (see Appendix V for details). Assuming the gas produced by the anaerobic decomposition is equal proportions of carbon dioxide and methane and that the methane is labelled to the same extent as the carbon dioxide, a mass balance indicates that, at the end of 22 days, 71% of the initial kraft pulp activity had appeared in the gas evolved and 44% of the initial activity of the simulated groundwood had similarly appeared. From these results it can be concluded that the system does decompose cellulose effectively.

The rate of decomposition of the kraft pulp was 1.6 times that of the simulated groundwood. This difference in rate of reaction may be influenced by differences in surface-to-volume ratios, amounts of cellulose present, presence of hemicelluloses, degree of crystallinity of pulps, degree of lignification of pulps, etc. No attempt was made to sort out the importance of these various factors. The photomicrographs shown in Fig. 24 show that the kraft pulp and the simulated groundwood have similar surface-to-volume ratios. Thus, as an order of magnitude, chemical pulps appear to decompose faster than groundwood pulps by a factor of approximately two.

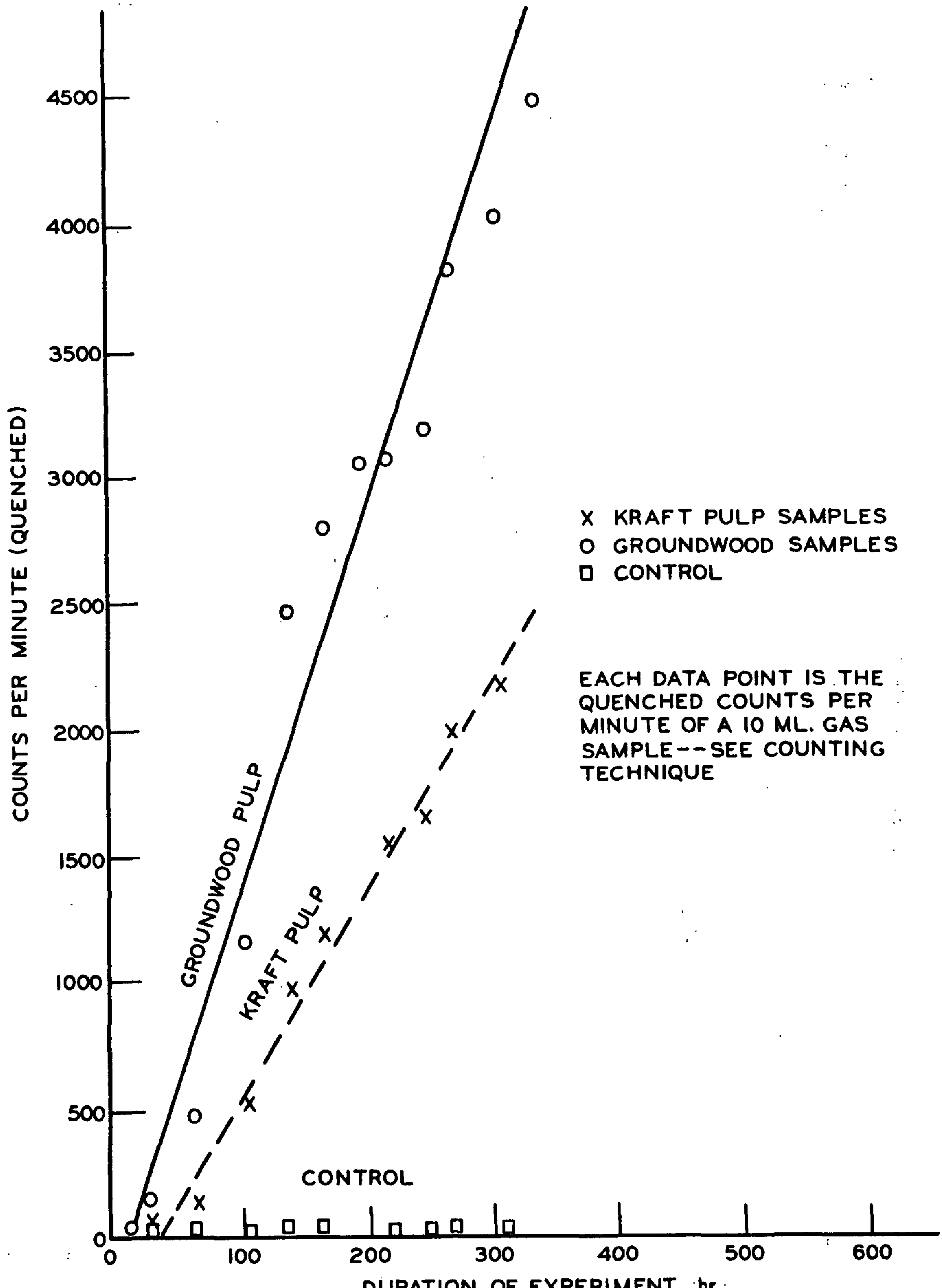


Figure 22. Quenched Counts per Minute of Gas Samples as Seen by ^{14}C Window

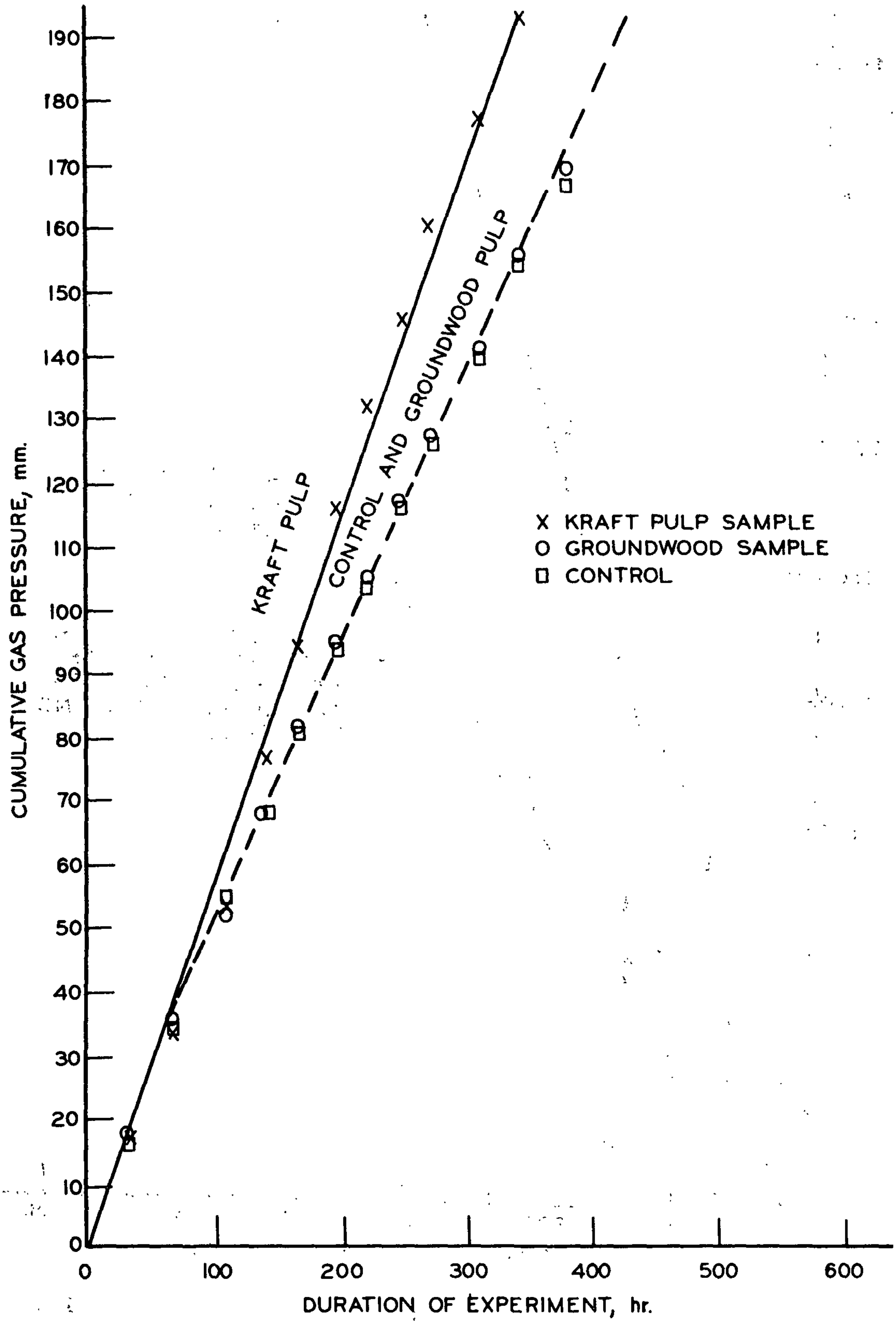


Figure 23. ^{14}C Decomposition Study Cumulative Pressure Data

TABLE XXVI

^{14}C EXPERIMENT DATA SUMMARY

		Solids					
Condition	pH ± 0.1[a]	VS, g. ± 0.002[a]	VS/FS ± 0.002[a]	Photo-micrographs	Final Bacteria, no./ml. $\pm 10\%$[a]	Glucose, g./l. ± 0.003[a]	Organic Acids, g./l. ± 0.02[a]
Kraft pulp	6.0	1.718	0.557	No	--	0.026[c]	0.00[c]
Kraft pulp	6.1	--[b]	--[b]	Yes	3.99×10^4		
Simulated groundwood	6.2	--[b]	--[b]	Yes	2.75×10^4	0.036[c]	0.00[c]
Simulated groundwood	6.2	1.791	0.587	No	--		
Control	6.2	--[b]	--[b]	Yes	4.56×10^4	0.022[c]	0.00[c]
Control	6.2	1.732	0.536	No	--		
Control corrected for added pulp		1.912	0.592				

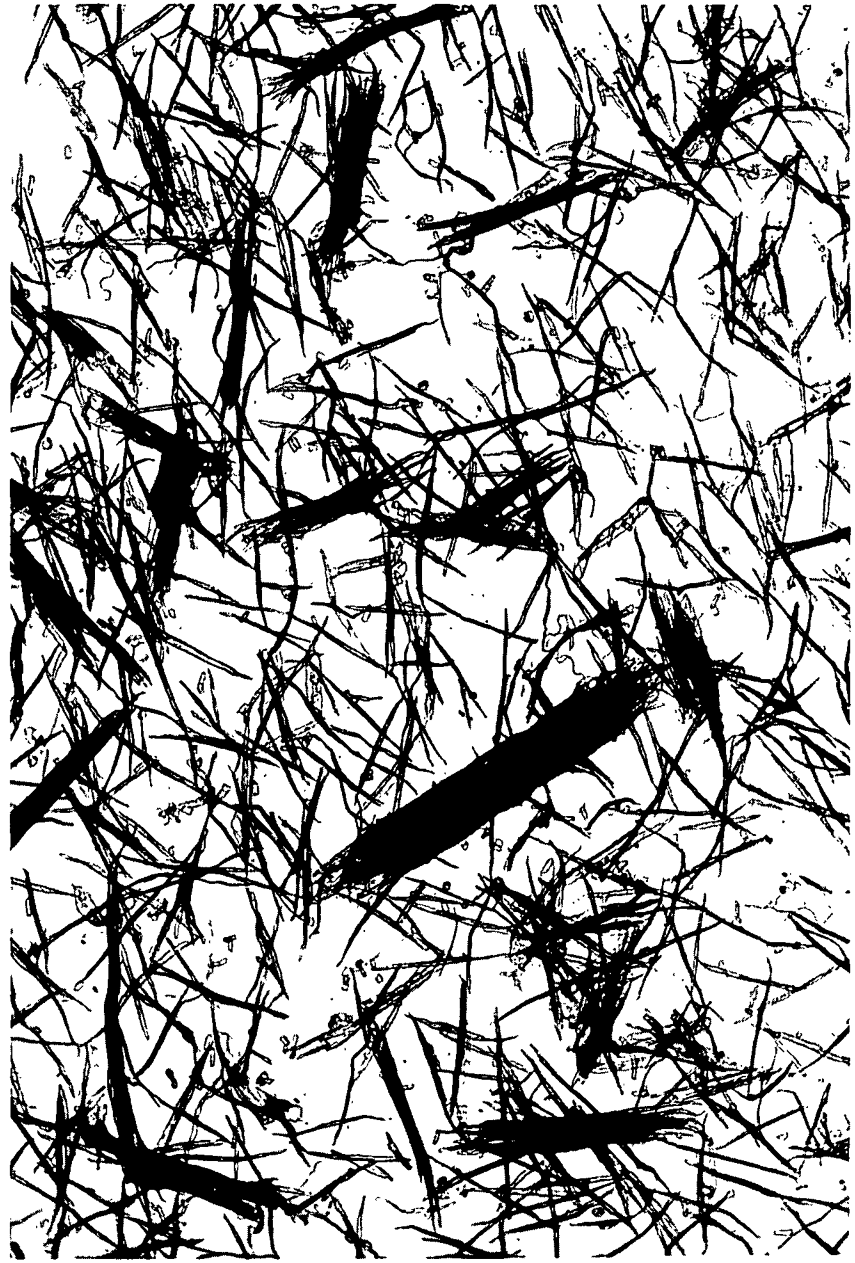
[a]Standard deviation.

[b]Samples of which photomicrographs were made were not available for solids analysis.

[c]Composite samples of the two flasks were analyzed.

Figure 23 shows that the simulated groundwood samples and the control had the same rate of gas evolution, and that the kraft pulp samples had a slightly higher rate. This is consistent with the concept that accessibility is important in controlling the rate of decomposition. At approximately the same surface-to-volume ratio the simulated groundwood pulp is less accessible because it is more highly lignified.

Simulated Groundwood 35X



Kraft Pulp 35X

Figure 24. Comparison of Surface-to-Volume Ratios

GLUCOSE AND CELLOBIOSE STIMULATION EXPERIMENTS

Another question suggested by the qualitative model for anaerobic decomposition concerns the rate-limiting step in the decomposition sequence. In order to establish the rate-limiting step, the following experiment was conducted. To separate 50-ml. sludge samples were added 0.20 g. glucose and 0.19 g. cellobiose, and the amount of gas produced as a function of time at two temperatures (10 and 25°C.) was monitored. (Less cellobiose than glucose was used so that the number of glycosidic units added to each system would be the same.)

The results are given in Fig. 25 and Table XXVII. The addition of glucose and cellobiose increased both the amount and the rate of gas evolution. The gas generated contained both methane and carbon dioxide. This indicates that the conversion of cellulose to glucose and/or cellobiose is the rate-limiting step in the decomposition sequence. This is consistent with the results of Chan (51), who worked with the continuous anaerobic fermentation of milled kraft pulp.

STIMULATED DECOMPOSITION EXPERIMENTS

The third question posed concerned how the bacterial anaerobic decomposition system in the river is affected by nutrient levels. The field studies demonstrated that there were sufficient quantities of nitrogen, phosphorus, and trace metals to support decomposition if these materials were present in a utilizable form. In order to establish whether the nutrients were in the correct form or were limiting factors, experiments involving the addition of supplementary quantities of nitrogen, phosphorus, and trace metal ions were carried out. These nutrients were in the optimum forms suggested by McCarty (32) for anaerobic digestion of sewage sludge.

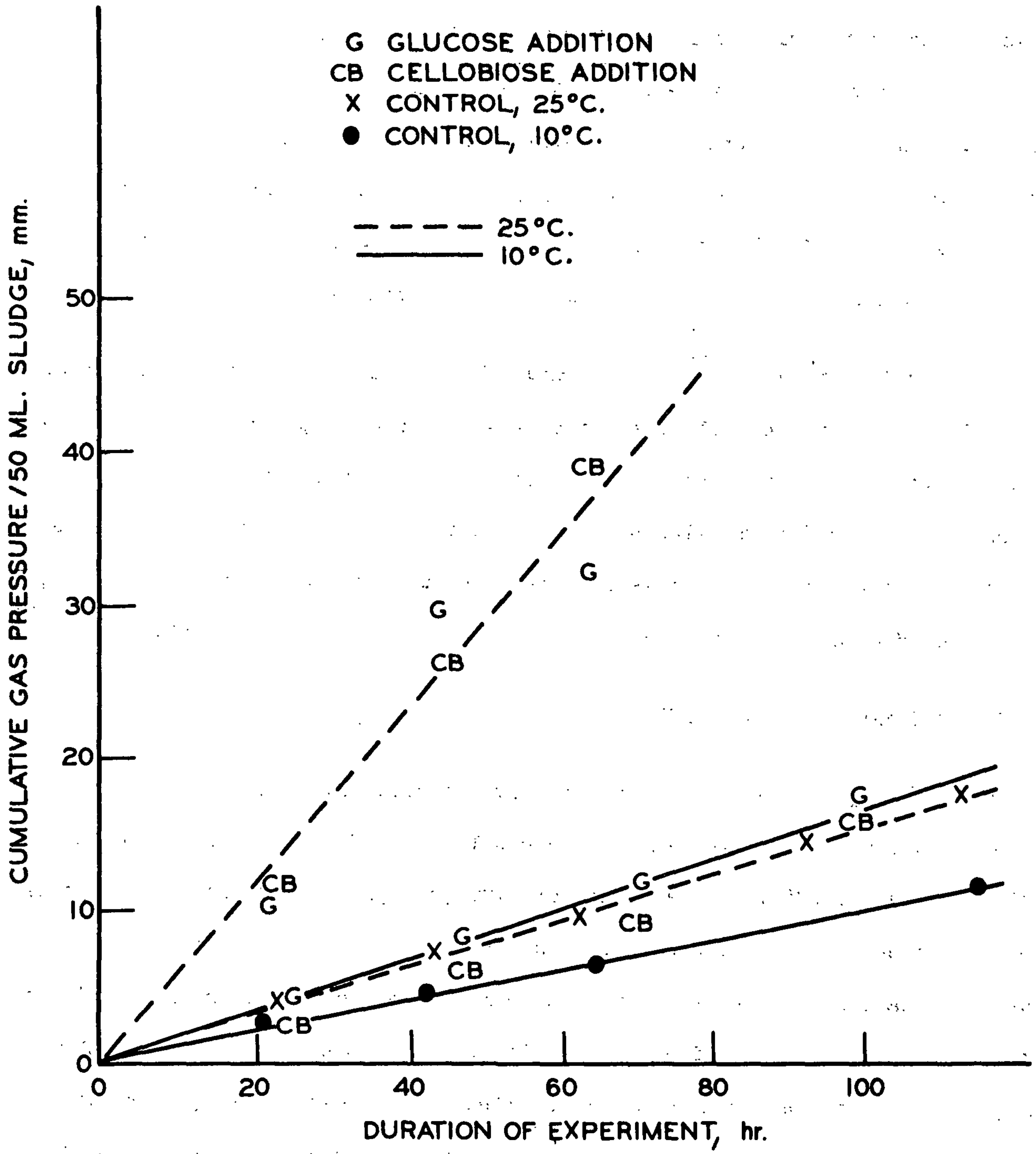


Figure 25. Stimulation of Gas Evolution by Addition of Glucose and Cellobiose

TABLE XXVII

SUMMARY OF DATA AT CONCLUSION OF GLUCOSE AND CELLOBIOSE STIMULATION EXPERIMENTS

Condition	pH ±0.1[b]	VS/FS ±0.005[b]	VS, g. ±0.003[b]	Acetic Acid, g./l. ±0.02[b]	Propionic Acid, g./l. ±0.02[b]	Glucose, g./l. ±0.003[b]	Bacteria Count, no./ml. $\pm10\%$[b]
10° Agitated[a]							
Glucose	4.8	0.524	2.561	0.51	0.40	0.010	--
Cellobiose	4.7	0.513	2.414	0.28	0.16	0.014	--
10° Stagnant[a]							
Glucose	6.7	0.455	2.237	0.25	0.18	0.037	--
Cellobiose	6.8	0.471	2.304	0.31	0.20	0.046	--
25° Agitated							
Glucose	6.1	--	--	0.44	0.00	0.018	1.75×10^5
Cellobiose	6.3	--	--	0.39	0.00	0.014	6.07×10^5
Control	5.9	0.878	1.561	0.12	--	0.019	3.65×10^4

[a]Controls for these conditions were part of the 10° temperature experiment, which were not tested for these parameters until after incubation at 15 and 20°C. as well. Only the cumulative gas pressure data was obtained for these controls.
[b]Standard deviation.

This experiment was conducted as follows: In each of seven reactors were placed 50 ml. of sludge (SXI). To two of these reactors were added 10 ml. of NH_4Cl solution (19.1 g./l.) and 10 ml. of sterile distilled water (designated H-N); to two were added 10 ml. of K_2HPO_4 solution (4.22 g./l.) and 10 ml. of sterile distilled water (designated H-P); to one were added one drop each of special salt solutions to give metal ion levels of 200 mg./l. calcium ($CaCl_2$), 100 mg./l. magnesium ($MgCl_2 \cdot 6H_2O$), 20 mg./l. iron ($FeCl_3 \cdot 6H_2O$), 20 mg./l. potassium (KCl), 25 mg./l. manganese ($MnSO_4 \cdot H_2O$), and 200 mg./l. sodium (NaCl), and 20 ml. of sterile distilled water (designated S); and to the two remaining reactors were added 20 ml. sterile distilled water so they could function as controls. The seven reactors were placed on the Warburg apparatus, purged with nitrogen, allowed to come to equilibrium, and sealed. The gas pressures (in mm.) were recorded daily.

The results of this experiment are given in Fig. 26 and Table XXVIII. It can be seen from Fig. 26 that the additions of positive metal ions as their chloride salts and of phosphate slightly stimulated the decomposition. The ammonium chloride addition, however, caused a suppression of the rate of gas evolution. The concentration of ammonium chloride in the reactor was 2.72 g./l., giving an ammonium ion concentration of 0.925 g./l. This is a rather high concentration of a substance which is known to be toxic to biological systems. This high level was chosen because McCarty (32) stated that this level of ammonium ion would not have an adverse effect on sewage sludge decomposition, but the river decomposition system must be different in its tolerance.

To get an estimate of the effect of nitrogen addition at a lower level, this portion of the experiment was repeated, using Sludge Sample SXIV and an ammonium ion concentration of 0.1 g./l. The results are shown in Fig. 27; slight stimulation was observed at this ammonium ion concentration. Sludge Sample XIV may be atypical, however, as will be discussed below in the sample variation studies; so this result may or may not be a general one.

The stimulated decomposition results demonstrated that the rate of decomposition of fiber in the river can be stimulated slightly by nutrient manipulation but that the system is not severely limited by lack of nutrients. Therefore, the nutrients measured in the river sludge samples probably are sufficiently accessible for utilization by the bacteria carrying out the anaerobic decomposition process.

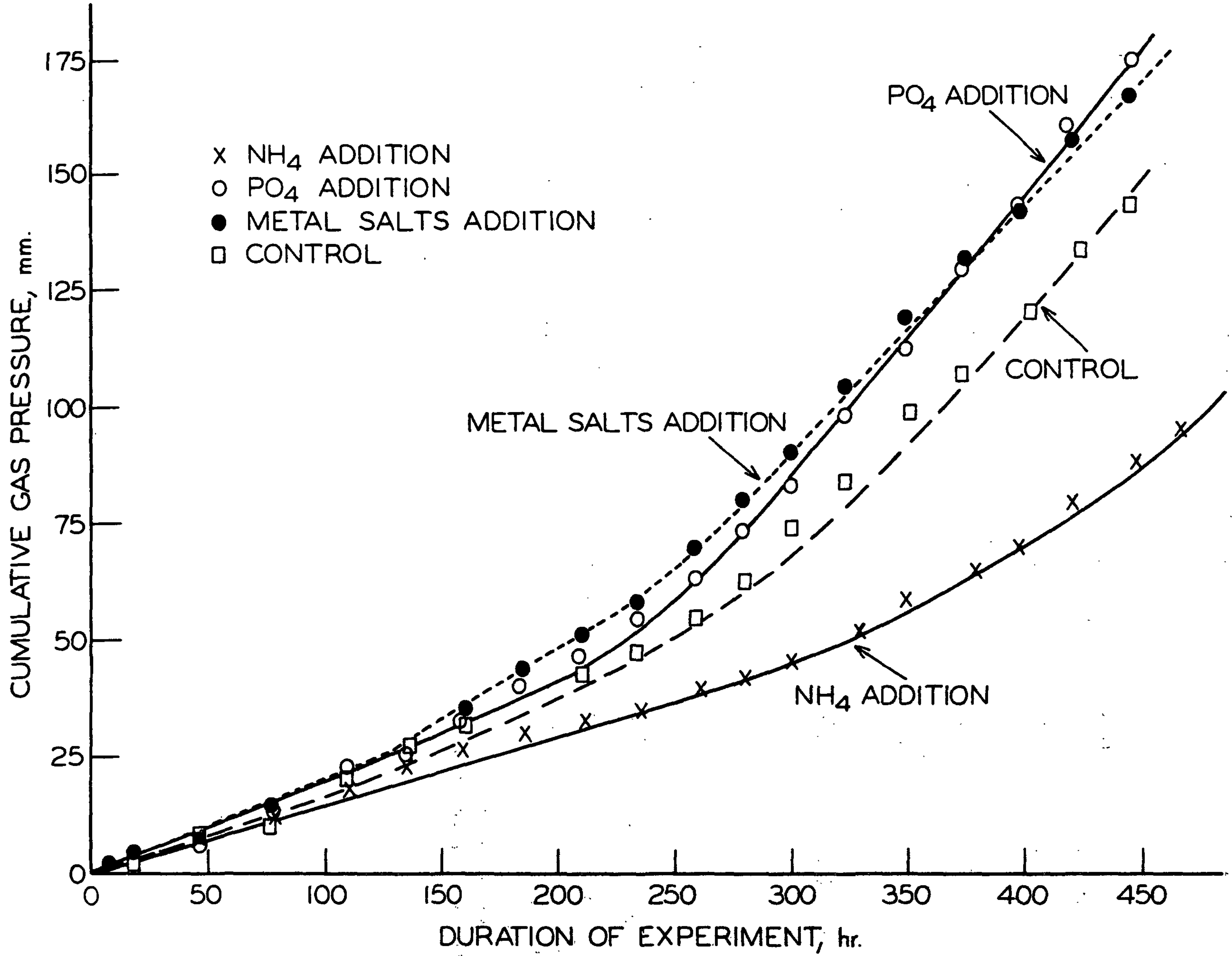


Figure 26. Stimulated Decomposition Experiments

TABLE XXVIII

SUMMARY OF RESULTS AT CONCLUSION OF STIMULATED DECOMPOSITION EXPERIMENTS

Condition	VS/FS $\pm 0.005^{a}$	VS, g. $\pm 0.003^{a}$	pH $\pm 0.1^{a}$	Glucose, g./l. $\pm 0.003^{a}$	Bacteria Count, no./ml. $\pm 10\%^{a}$	Organic Acids, g./l.
H-N (0.925 g./l.)	0.667	1.895	6.35	0.010	1.75×10^{5}	None to trace
H-P	0.688	1.793	6.2	0.006	0.3×10^{5}	None to trace
S	0.671	1.780	6.3	0.003	6.22×10^{5}	None to trace
Control SXI	0.631	1.891	6.3	0.008	1.96×10^{5}	None to trace
						Acetic Acid, g./l. $\pm 0.02^{a}$
H-N (0.1 g./l.)	0.801	1.406	5.6	0.024	1.69×10^{4}	0.24
Stagnant SXIV	0.849	1.452	6.3	0.018	1.20×10^{6}	0.33
Control SXIV	0.878	1.561	5.9	0.019	3.65×10^{4}	0.12

[a]Standard deviation.

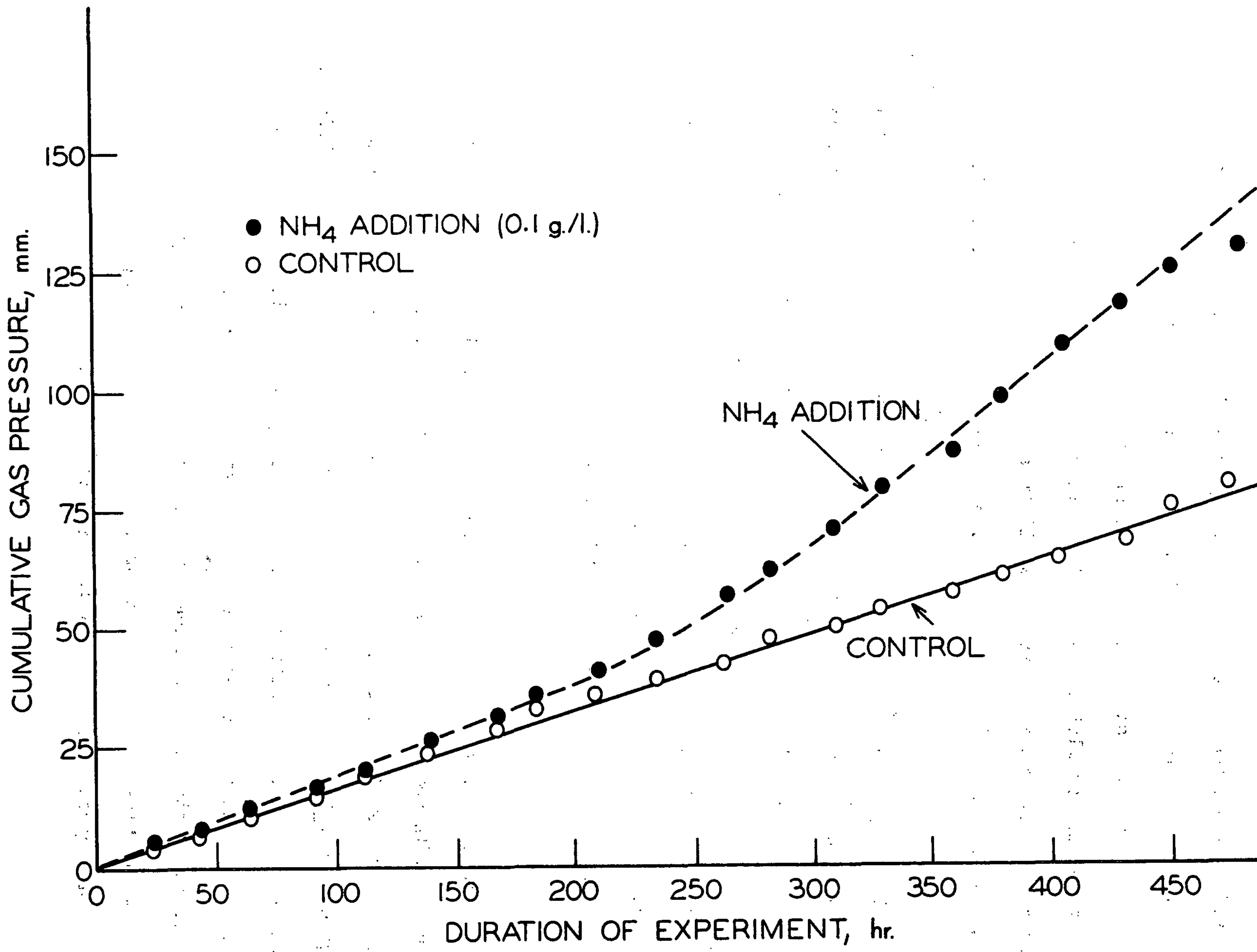


Figure 27. Stimulated Decomposition Experiments

TEMPERATURE STUDY

Temperature is another important variable which affects the rate of reaction. The field data showed the temperature range experienced by the sludge bed over a yearly cycle was from 1 to 30°C. Some of the previous experiments of this investigation were conducted at 25°C., so information on rates of decomposition at that temperature were available. In addition to these data, the rates of decomposition of sludge material were determined at 10 (the lower limit of the experimental equipment), 15, and 20°C. These experiments were conducted in the following manner: With the Warburg bath temperature at 10°C., four reactors, each containing 50 ml. of sludge and 20 ml. of sterile distilled water, were placed in the bath. Two were agitated and two stagnant. These reactors were observed for two weeks to establish a rate of gas evolution. After two weeks the bath temperature was raised to 15°C. and four more similarly prepared reactors added, two agitated and two stagnant. The initial four reactors were also left in the bath. After two more weeks the temperature was raised to 20°C., again adding two agitated and two stagnant reactors and leaving the previous eight reactors in place.

The results of this set of experiments are summarized in Fig. 28 through 31 and Tables XXIX and XXX. In the literature some investigators postulate the existence of a 20°C. temperature threshold for the anaerobic decomposition of sewage sludge (42). As can be seen from Fig. 28 and 29, no such threshold existed for the anaerobic decomposition of fibrous sludge from this river system. The rate of decomposition increased with temperature over the range investigated. The rate constants were determined from the slope of the straight line. If the data shown in Fig. 30 are extrapolated, a zero rate of decomposition is predicted to occur at approximately 4 to 5°C. This point could be considered a temperature

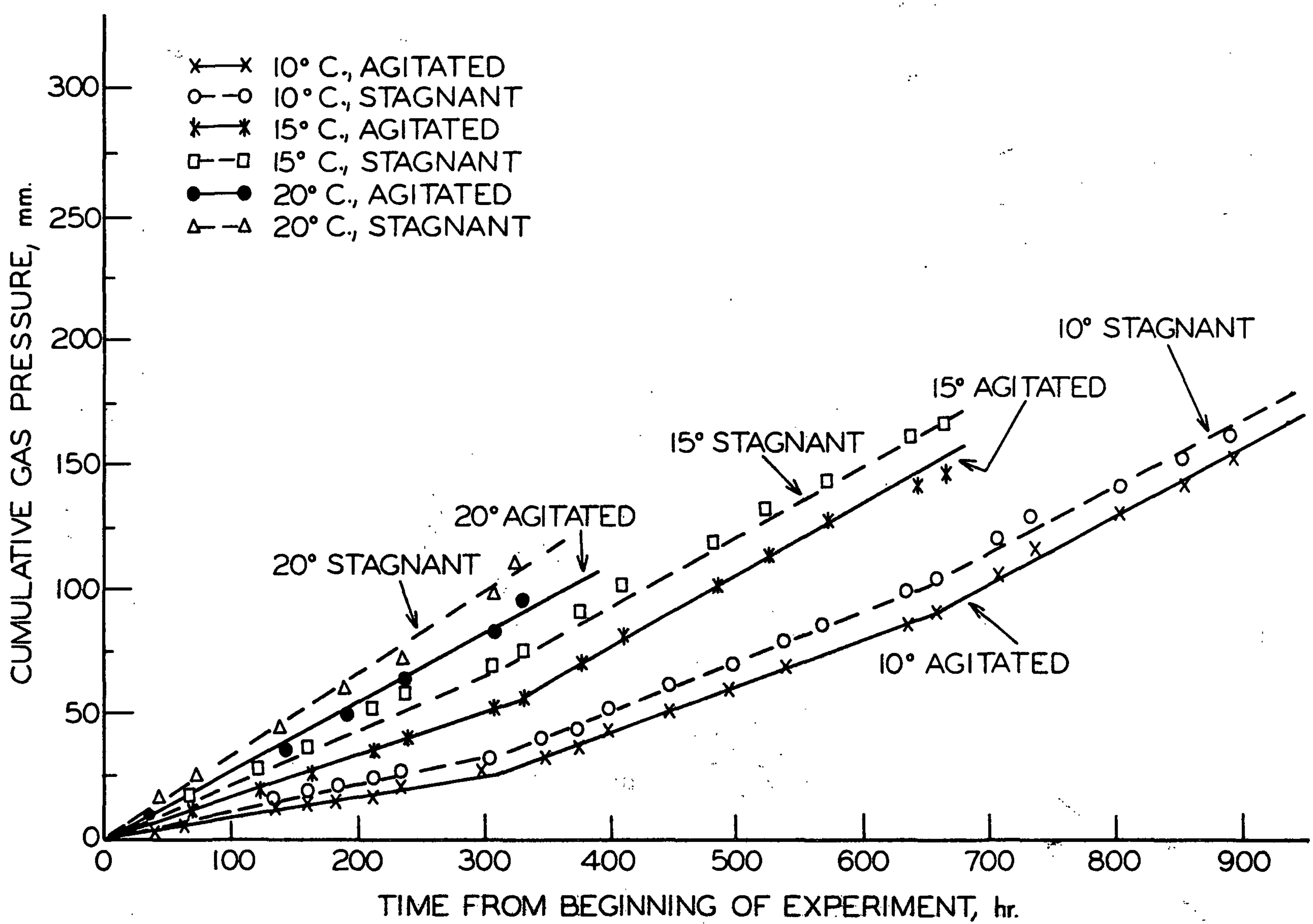


Figure 28. Effect of Temperature on Rate of Decomposition

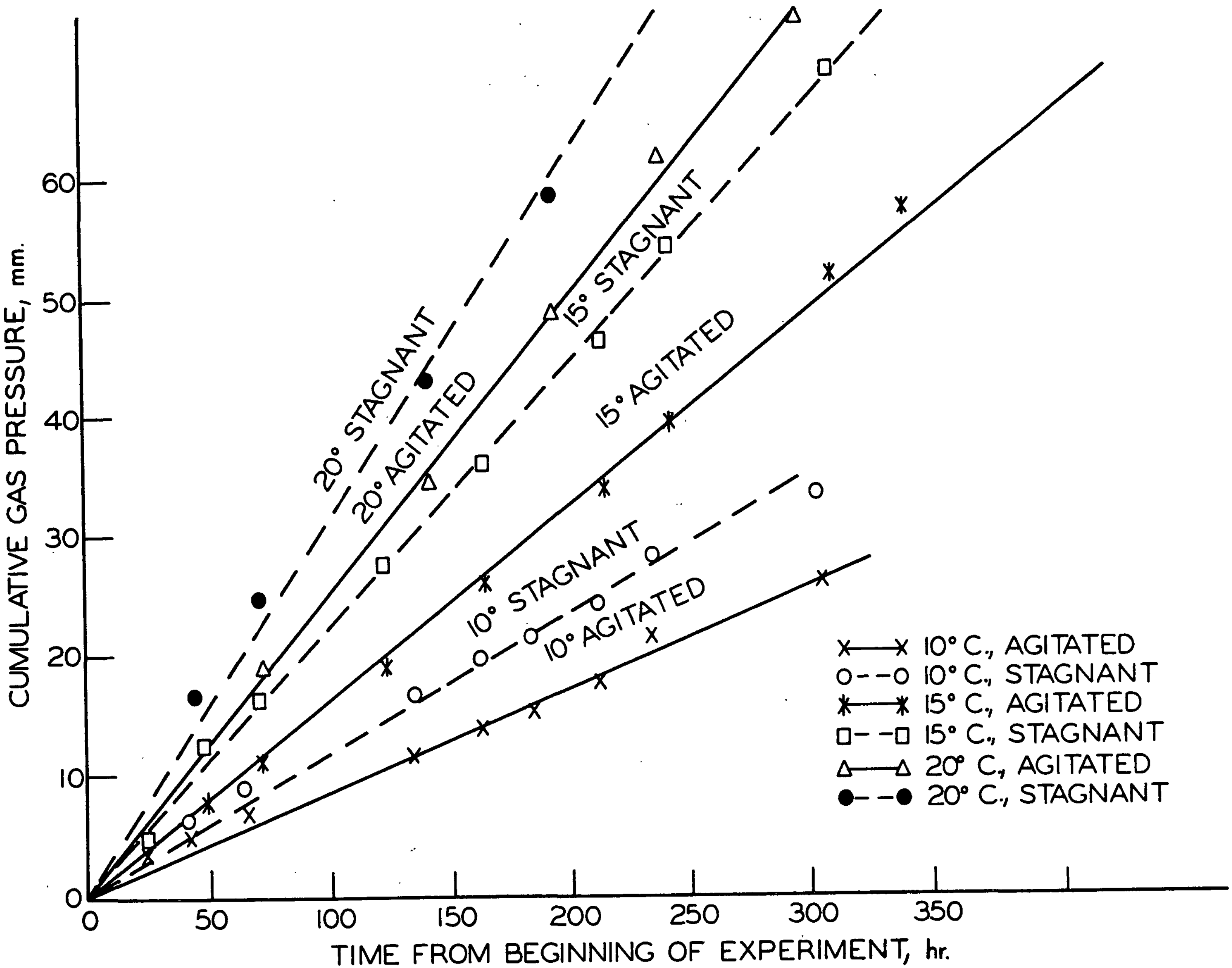


Figure 29. Effect of Temperature on Rate of Decomposition (Initial Portions of Curves Shown in Fig. 25 Expanded Scale)

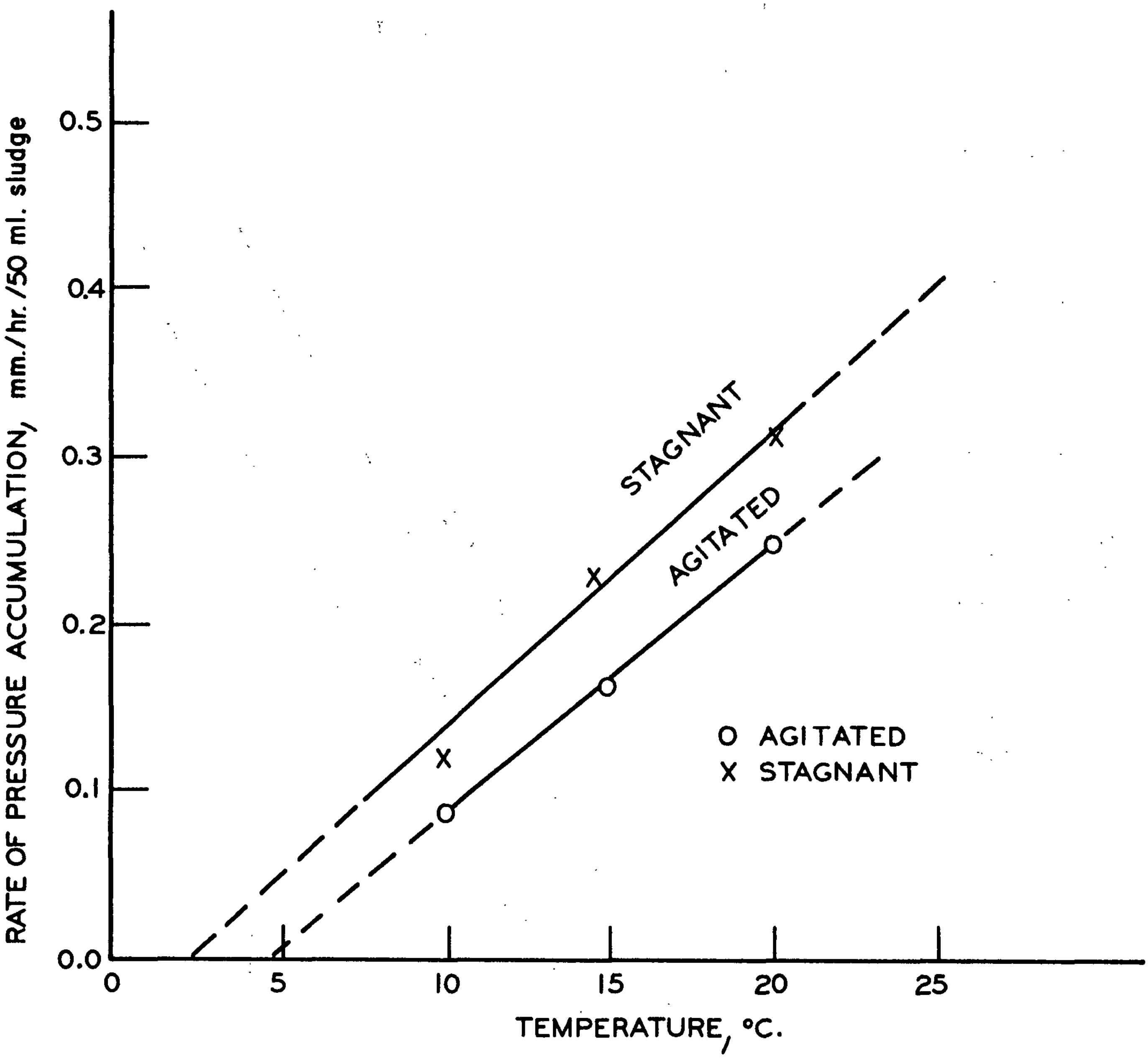


Figure 30. Effect of Temperature on Rate of Gas Production

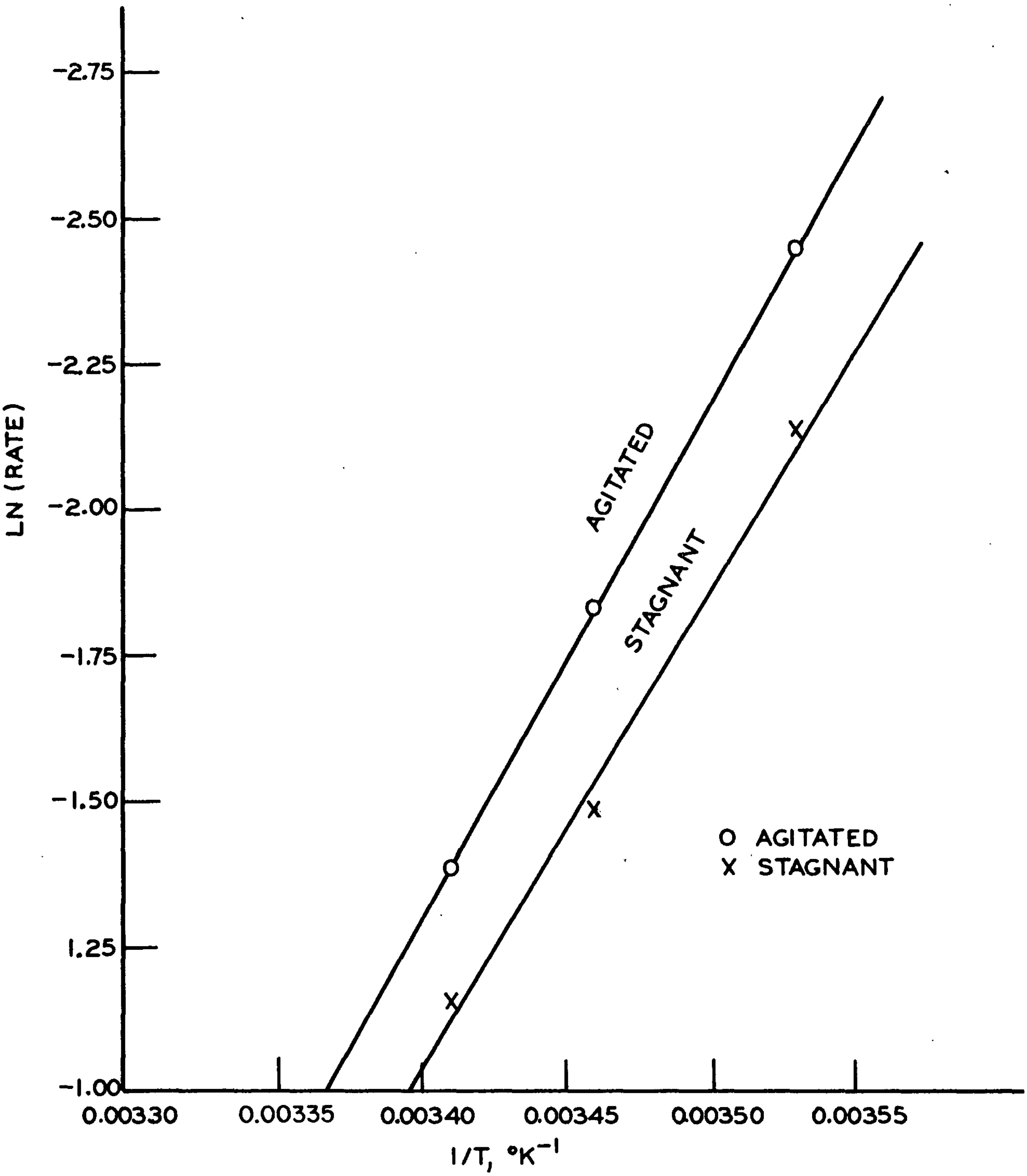


Figure 31. Temperature Data in Form of Arrhenius Equation

TABLE XXIX

SUMMARY OF RATE DATA FROM TEMPERATURE STUDY

Temperature °C.	Temperature °K	Stagnant Rate, mm./hr./50 ml. sludge	Agitated Rate, mm./hr./50 ml. sludge
10	283	12.0×10^{-2}	8.7×10^{-2}
15	288	23.0×10^{-2}	16.3×10^{-2}
20	293	31.1×10^{-2}	25.2×10^{-2}

	Stagnant	Agitated
Slope of linear approximation of rate *vs.* temperature curve, mm./hr./50 ml./°C.	1.6×10^{-2}	1.9×10^{-2}
Slope of Arrhenius plot	8.32×10^{3}	8.8×10^{3}
Energy of activation, cal./mole	16.5×10^{3}	17.5×10^{3}

TABLE XXX

SUMMARY OF DATA AT END OF TEMPERATURE STUDY

Condition	Rate, mm./hr./50 ml.	VS/FS ±0.005[a]	VS, g. ±0.003[a]	pH ±0.1[a]	Glucose, g./l. ±0.003[a]	Bacteria Count, no./ml. ±10%[a]	Organic Acids, g./l.
Stagnant 10 to 15 to 20	0.12	0.420	2.358	6.2	0.010	1.5×10^{5}	None
Stagnant 15 to 20	0.23	0.409	2.038	6.4	0.011	1.09×10^{5}	None
Stagnant 20	0.31	0.536	2.397	6.2	0.011	1.25×10^{6}	None
Agitated 10 to 15 to 20	0.087	0.473	2.371	6.1	0.011	3.99×10^{4}	None
Agitated 15 to 20	0.163	0.489	2.275	6.3	0.011	7.0×10^{4}	None
Agitated 20	0.252	0.609	2.288	6.2	0.011	2.9×10^{4}	None

[a]Standard deviation.

threshold, but it is based on extrapolation; the actual rate may not drop to zero at this point. Figure 30 is a linear plot and illustrates that the data are approximately linear over the range of temperature investigated. The actual relation between temperature and rate may not be linear, but if it is nonlinear it is not highly curved in this temperature range.

In addition to the effect of temperature on decomposition, Fig. 28 illustrates that sudden changes in temperature (5° at a rate of 1° per 6 min.) did not cause inhibition of the decomposition process.

Figure 31 is a plot of the temperature-rate data in terms of the Arrhenius rate equation. The calculated Arrhenius activation energies which are given in Table XXIX are 16.5 kcal./mole for the stagnant reactors and 17.5 kcal./mole for the agitated reactors. These activation energies fall in the normal range of energies for chemical reactions.

The high activation energies rule out the possibility that diffusion limits the rate of decomposition. Diffusion would be the only mechanism of mass transfer operating in the interstices of the sludge bed. The permeability of the sludge material is so low, the beds are of such long length, and the only driving force so small (the slope of the river bottom), that flow is nonexistent. See Appendix VI for a full discussion of the mass transfer considerations.

The unimportance of mass transfer in limiting the decomposition process is reinforced by the effect of agitation on the decomposition rate. At 10, 15, and 20°C. the agitated samples had slightly lower rates than did the nonagitated samples. Results on other sludge samples at 25°C. showed that the agitated and nonagitated samples had comparable rates for the first two weeks. If the system were limited by mass transfer, agitation would have been expected to increase the rate of decomposition. The difference between agitated and nonagitated conditions may be related to adjustments in the bacterial population, because the agitated vessels always had lower thioglycolate bacteria counts than did the nonagitated vessels (see Table XXX). Agitation may also inhibit the transfer of intermediates between the various stages of the decomposition process at a reaction site.

SAMPLE VARIATION STUDY

With one exception, a single sample of sludge was used in performing each of the above sets of laboratory studies, so that each experiment was internally consistent. In the stimulated decomposition experiments, where two different sludge samples were used, comparisons between the experiments were difficult to make. This led to the question of how much variation does exist between monthly sludge samples and between samples from different locations in the river with regard to their rates of decomposition.

Duplicate 50-ml. samples from five different monthly river visits and from five different river locations were run on the Warburg apparatus at 25°C. to determine the between-sample variability in the rate of decomposition.

Figure 32 illustrates that there were large variations in the rates of decomposition between monthly samples. The variation in rate does not seem to correlate with any single factor monitored, as can be seen from Table XXXI. What seems most likely is that several factors enter into determining the overall rate of decomposition. From visit to visit, the type of fiber, particle size distribution, level of nitrogen, level of phosphorus, buffering capacity of the system, etc., all vary; and all of these factors may influence the overall rate.

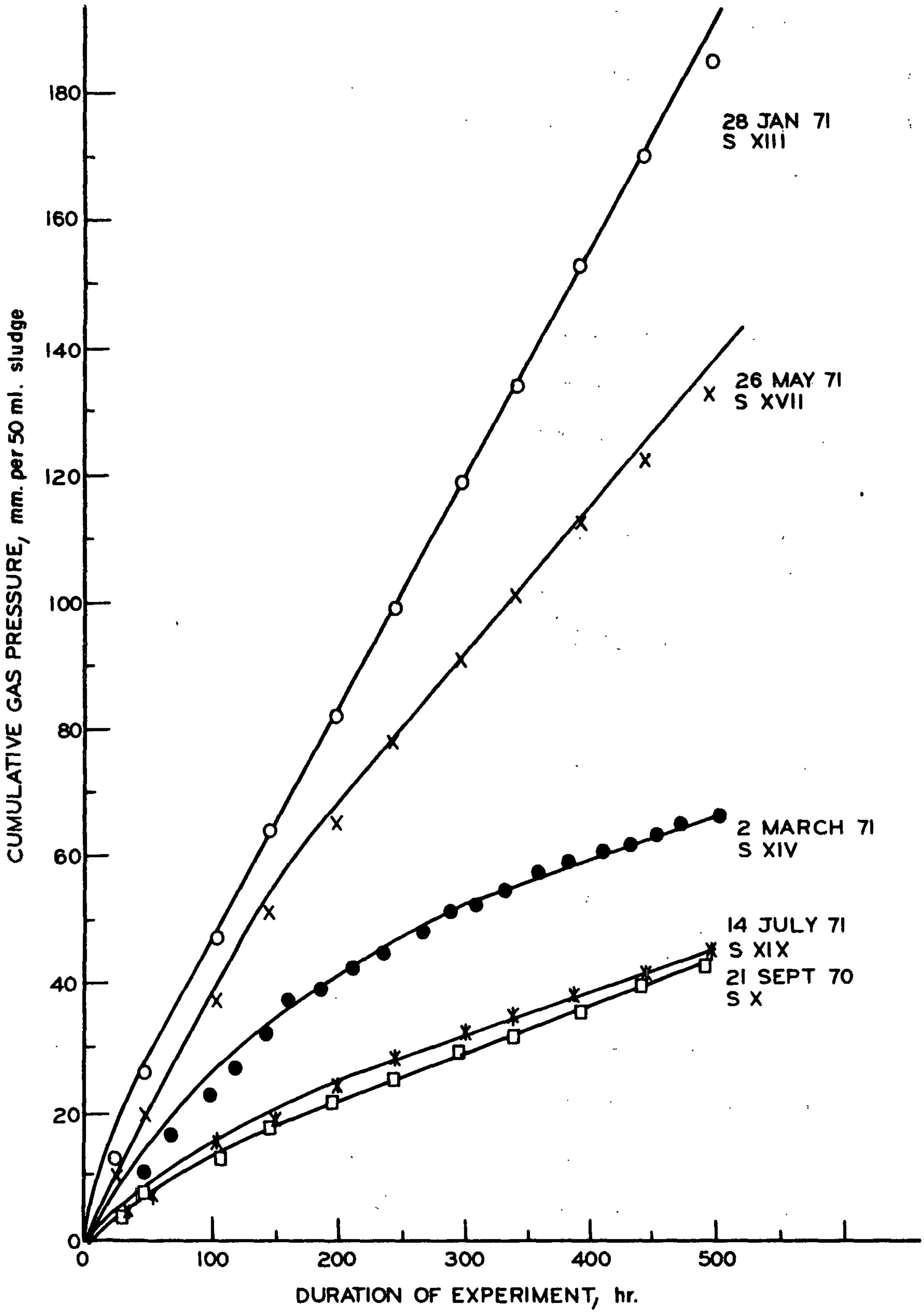


Figure 32. Rate Variation Between Monthly Samples

TABLE XXXI

SUMMARY OF DATA FROM SAMPLE VARIATION STUDY

A. Different Monthly Sludge Samples

	21 Sept. 70 SX	28 Jan. 71 SXIII	2 March 71 SXIV	26 May 71 SXVII	14 July 71[a] SXIX
Initial VS, as % TS (±0.2)	35.2	48.1	53.1	31.4	21.2
Organic nitrogen, as % TS (±0.01)	0.51	0.66	0.58	--	--
Mg. N/g. VS (±0.1)	19.9	13.7	11.0	--	--
Mg. P/g. VS (±1)	10.3	11.0	7.1	--	--
Final VS, as % TS (±0.2)	26.1	36.0	45.7	28.2	19.7
Final TS, g. (±0.02)	7.83	4.70	3.16	11.36	12.95
pH (±0.1)	6.45	5.9	6.3	5.8	6.0
Bacteria count, no./ml. (±10%)	1.25×10^5	0.8×10^5	12.0×10^5	1.57×10^5	3.88×10^5
Glucose, g./l. (±0.003)	0.004	0.009	--	0.008	0.008
Acetic acid, g./l. (±0.02)	0.00	0.00	0.33	0.00	0.00
Propionic acid, g./l. (±0.02)	0.00	0.00	0.00	0.00	0.00
Decomposition rate, mm./hr./50 ml. sludge	0.07	0.36	0.08	0.22	0.07
Decomposition rate, mm./hr./g. VS	0.00343	0.213	--	0.069	0.0274

See end of table for footnotes.

TABLE XXXI (Continued)

SUMMARY OF DATA FROM SAMPLE VARIATION STUDY

B. Samples from Different River Locations

	B 1-3	B 6-3[b]	B 14-3	B 22-3	B 24-3
Initial VS, as % TS (±0.2)	41.0	21.2	37.8	16.1	24.2
Final VS, as % TS (±0.2)	39.6	19.7	39.1	19.5	31.1
Final TS, g. (±0.02)	2.57	12.95	4.42	12.35	5.85
pH (±0.1)	5.7	6.0	6.3	6.5	6.65
Bacteria count, no./ml. (±10%)	0.32×10^5	3.88×10^5	1.16×10^5	0.53×10^5	20.9×10^5
Glucose, g./l. (±0.003)	0.009	0.008	0.013	0.006	0.022
Acetic acid, g./l. (±0.02)	0.00	0.00	0.00	0.00	0.00
Propionic acid, g./l. (±0.02)	0.00	0.00	0.00	0.00	0.00
Mercury, p.p.m. of ovendry solids	5.72	11.1	5.98	55.0	4.54
Decomposition rate, mm./hr./50 ml. sludge	0.20	0.07	0.08	0.001	0.048
Decomposition rate, mm./hr./g. VS	0.196	0.0274	0.0462	0.000414	0.0263

[a]This sample is B 6-3.

[b]This sample is 14 July 71, SXIX.

If the sample of 2 March 1971 is not considered, there is a relationship between rate and time of the year which could be explained on the basis of the effect of fresh fiber build-up over the winter. The March sample was unusual in that it had an exceptionally high ratio of volatile solids to fixed solids, thioglycolate bacteria count, and acetic acid content; it may represent a system on the verge of becoming unbalanced with regard to acid production and acid consumption. In the literature of anaerobic decomposition this would be called a "stuck digester."

The range of rates found in this study are compared with those reported by other investigators for the anaerobic decomposition of cellulose in Table VII of the Literature Review (p. 19).

Figure 33 shows the rates of decomposition found for samples taken from different river positions. There is considerable variation of rate between these samples. The samples seem to fall into three groups: B 1-3; B 6-3, B 14-3, and B 24-3; and B 22-3. B 1 is a bed in Little Lake Butte des Morts which is unique in that its fiber component is mainly chemical pulp. It is reasonable that this bed should have a higher decomposition rate than the other beds, whose fiber is mainly groundwood. The sample with a low rate of decomposition, from B 22, came from a bed located below the old Charmin Paper Co. mill which is no longer operating. This bed must therefore consist only of redeposited fiber, fiber which has been transported from other upriver beds through scour and flotation. The redeposited fiber would be expected to decompose more slowly because its more accessible cellulose would have been partially decomposed already in its first location. This bed also had a very high mercury concentration, which may also have a suppressive effect on the rate of decomposition.

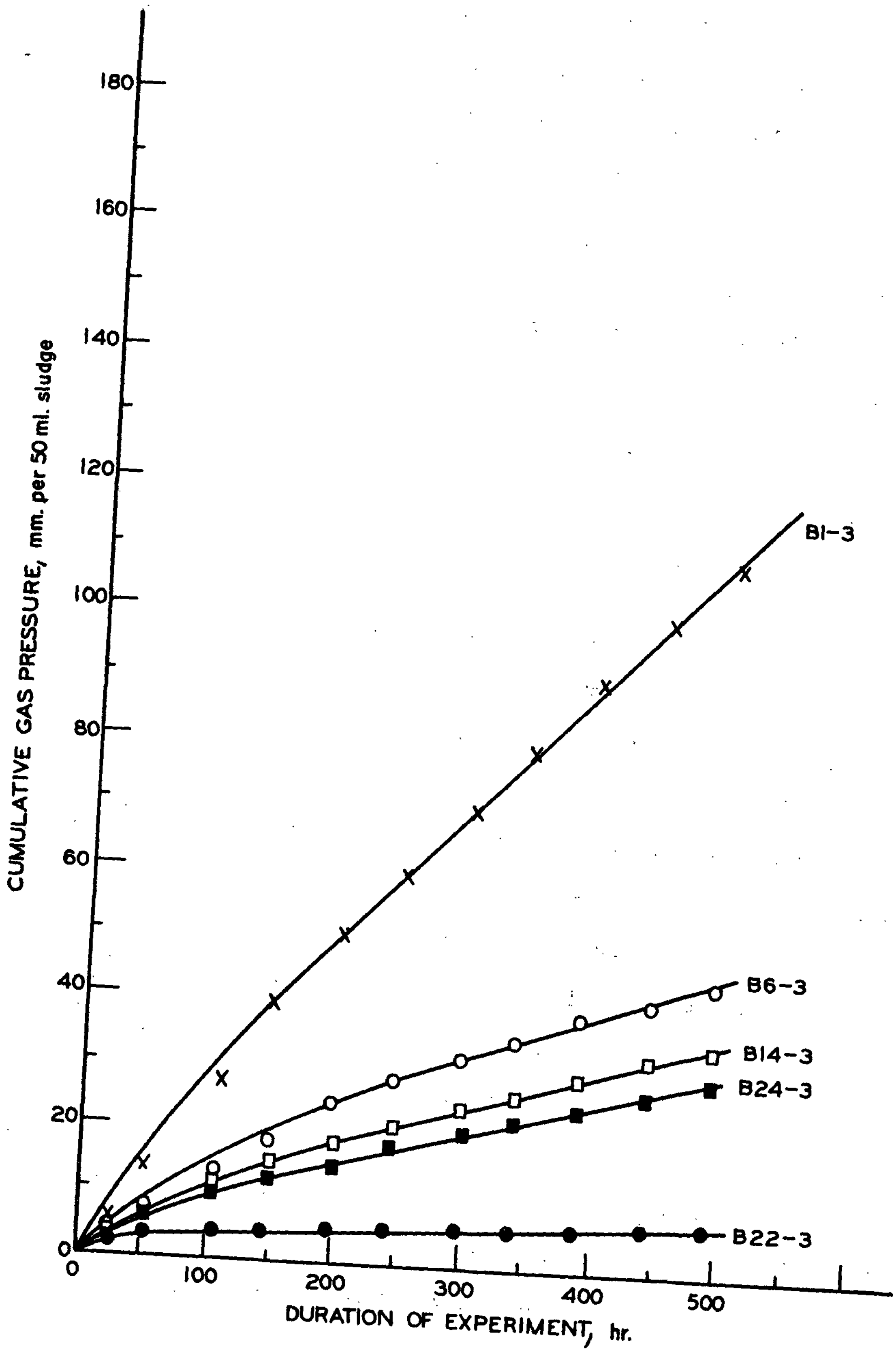


Figure 33. Rate Variation Between Sludge Samples Taken from Various River Locations on July 14 and 15, 1971

It may be that all the rates found in this river position study are low because the sampling was performed in mid-July after the greater portion of the active summer decomposition had already taken place, resulting in the depletion of the more easily decomposed material.

GAS COMPOSITION

All of the Warburg data presented above have been in the form of pressure of gas evolved in mm. of mercury. The pressure can be converted to ml. of gas evolved by application of the ideal gas law and compensation for solubility of the gas in the liquid phase of the reactor by use of Henry's law. In order to be able to compensate for gas solubility, the gas composition had to be determined by use of gas chromatography. A computer program was written to perform the conversion from pressure to volume of gas evolved. The program and all of the results are presented in Appendix VII; an overall summary of the results is given in Table XXXII. This table indicates that the composition of the gas evolved by the decomposition process was approximately half methane and half carbon dioxide. This composition of gas from anaerobic fermentation of carbohydrate has been reported previously in the literature (55).

BED LIFE PREDICTIONS

If the gas composition data are used to convert the rate of pressure generation data from the sample variation study into rate of mass removal data, predictions of bed life can be made. In order to compensate for temperature variations found in the natural system, conservative assumptions about the response of the system to temperature are made based on the temperature study. Table XXXIII gives these approximations and shows that a bed life of one to two years can be predicted for sludge beds in the Lower Fox River, assuming that no further addition of fiber is made to the system over this period.

TABLE XXXII

SUMMARY OF GAS COMPOSITION CALCULATIONS

	Average $CH_4:CO_2$ Ratio in Reactor	Average Fraction Methane Evolved	Total Gas Evolved During Monitoring Period, ml. at STP
^{14}C study:			
Kraft pulp + SXIII	1.0	0.50	293.9
Simulated ground-wood + SXIII	1.1	0.52	244.1
Control SXIII	1.1	0.51	229.0
Sample variation study:			
B 1 (highest)	1.1	0.54	137.1
B 22 (lowest)	0.68	0.82	7.2
SXIII (highest)	1.0	0.51	227.7
SX (lowest)	1.2	0.62	45.9
Temperature study:			
10° Agitated	1.0	0.49	25.8
Stagnant	0.63	0.61	33.4
15° Agitated	1.3	0.57	58.5
Stagnant	1.4	0.53	75.6
20° Agitated	0.93	0.53	109.8
Stagnant	0.86	0.51	124.1

TABLE XXXIII

ANAEROBIC BED LIFE CALCULATIONS

The range of rates obtained from the sample variation study was used for the calculations.

Lowest Rate Estimate: (Sample SX)

Rate of pressure generation: 0.076 mm./hr.
Volatile solids: 25.6% of total solids
Conversion from rate of pressure generation to rate of mass removal:
0.076 mm./hr. x 1.0 ml./mm. x 1.34×10^{-3} g./ml. =
1.02×10^{-4} g./hr. (based on 50 ml. sludge)
Calculation of amount of VS initially in Warburg flask:
50 ml. x 0.05 g./ml. x 0.256 = 0.64 g. VS
Calculation of time required to convert all VS to gas, assuming zero order kinetics:
$0.64/1.02 \times 10^{-4} = 6.27 \times 10^{3}$ hr. = 261 days = 8.7 months

Highest Rate Estimate: (Sample SXIII)

Rate of pressure generation: 0.330 mm./hr.
Volatile solids: 48.1% of total solids
Conversion from rate of pressure generation to rate of mass removal:
0.330 mm./hr. x 1.0 ml./mm. x 1.34×10^{-3} g./ml. =
4.42×10^{-4} g./hr. (based on 50 ml. sludge)
Calculation of amount of VS initially in Warburg flask:
50 ml. x 0.05 g./ml. x 0.481 = 1.21 g. VS
Calculation of time required to convert all VS to gas, assuming zero order kinetics:
$1.21/4.42 \times 10^{-4} = 2.73 \times 10^{3}$ hr. = 114 days = 3.8 months

If it is assumed that the year consists of two months at 25°C. (or more) and five months at 15°C., with no decomposition occurring during the remaining five months, and that the rate at 15°C. is approximately 1/3 that at 25°C., an approximate bed life of one to two years (i.e., two to four months at 25°C. and five to ten months at 15°C.) would be predicted, assuming also that no new fibrous material is added during this time.

If these same mass removal data are used to perform a mass balance between volatile solids added from mill sources and volatile solids destroyed by anaerobic decomposition, an interesting result is obtained. The rate at which volatile solids are destroyed by anaerobic decomposition will almost balance the rate of volatile solids addition by the mills, if the 1972 Wisconsin Department of Natural Resources water quality standards are met. This mass balance is given in Table XXXIV. It must be remembered that even under this equilibrium condition the normal patterns of behavior will still be observed in the river system. There will be build-up of the fiber content of sludge during the winter months when the rate of addition exceeds the rate of decomposition, the beds will be scoured and redistributed during the spring run-off, and the active decomposition during the summer months will still produce gases and floating sludge. Overall the decomposition will keep pace with the addition; however, there should be little year-to-year accumulation of volatile matter on the river bottom.

TABLE XXXIV

MASS BALANCE OF MILL VOLATILE SOLIDS ADDITION AND ANAEROBIC DECOMPOSITION FOR THE LOWER FOX RIVER

Mill Input

Total mill volatile solids input if 1972 DNR standards are met = 1.01×10^5 lb./day[a] x 365 days = 3.68×10^7 lb./yr.

Destruction by Anaerobic Decomposition

Assumptions

1. 50% of river bottom covered with sludge to a depth of 1 ft.
2. Decomposition at 25°C. for two months and at 15°C. for five months, with none occurring during the remaining five months of the year

High Rate Estimate (SXIII)

Calculation of the amount of material decomposed per day by anaerobic decomposition at 25°C.:

Rate of decomposition: 1.35×10^{-2} lb./ft.^{3}/day
Area covered with sludge: 1.05×10^8 ft.^{2}
Sludge depth: 1.0 ft.
1.35×10^{-2} lb./ft.^{3}/day x 1.05×10^8 ft.^{2} x 1.0 ft. = 1.42×10^6 lb./day

Total amount of destruction at 25°C.:

1.42×10^6 lb./day x 60 days = 8.52×10^7 lb. VS

Total amount of destruction at 15°C. (at 1/3 the above rate):

$1.42 \times 10^6/3$ lb./day x 150 days = 7.10×10^7 lb. VS

Total = 1.56×10^8 lb., which is greater than the amount added by the mills in one year

Low Rate Estimate (SX)

Calculation of the amount of material decomposed per day by anaerobic decomposition at 25°C.: (as above)

3.08×10^{-3} lb./ft.^{3}/day x 1.05×10^8 ft.^{3} x 1.0 ft. = 3.24×10^5 lb./day

Total amount of destruction at 25°C.:

3.24×10^5 lb./day x 60 days = 1.94×10^7 lb. VS

TABLE XXXIV (Continued)

MASS BALANCE OF MILL VOLATILE SOLIDS ADDITION AND ANAEROBIC DECOMPOSITION FOR THE LOWER FOX RIVER

Low Rate Estimate (SX) (cont'd)

Total amount of destruction at 15°C. (at 1/3 the above rate):

$3.24 \times 10^5/3$ lb./day x 150 days = 1.62×10^7 lb. VS

Total = 3.56×10^7 lb., which is 96.6% of the amount added by the mills in one year

Therefore, it can be concluded that anaerobic decomposition would destroy an appreciable fraction, if not all, of the fiber added to the river by the mills each year under the 1972 DNR standards.

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[a]The allowable total solids of each mill are set by the DNR. This total was multiplied by the average VS/FS ratio for that type of mill in the state of Wisconsin to get the VS. These daily VS values were added to obtain this figure as the total VS input per day by mills along the Lower Fox River.

CONCLUSIONS

The Lower Fox River has an appreciable fraction of its bottom covered with fibrous sludge; river surveys indicated approximately 50% coverage. These beds disappear from a given location by three principal mechanisms: scour, flotation, and decomposition. Approximately 4/5 of the Lower Fox River is subject to bed scour and redistribution; the remaining 1/5 either contains permanent beds or is always free of sludge.

The principal mechanism for sludge bed destruction is decomposition, since scour and flotation merely relocate the sludge in another river position. This decomposition is mainly anaerobic rather than aerobic. The anaerobic decomposition system operating in the Lower Fox River is not seriously limited by lack of nutrients, nor is it limited by mass transfer. The rate-limiting step in the anaerobic decomposition sequence is the breaking down of cellulose into glucose and/or cellobiose. Chemical pulps anaerobically decompose about twice as fast as do groundwood pulps with similar surface-to-volume ratios.

Temperature has an appreciable effect on the rate of decomposition. The temperature profile in the bed is determined primarily by heat conduction. This profile is linear, indicating that the energy generated by the decomposition process is negligible compared with that conducted in from outside the bed. Sudden changes in temperature within a 5°C. range do not cause inhibition of the anaerobic decomposition of fibrous sludge. The rate of gas production increases linearly with temperature over the range from 10 to 25°C., approximately threefold for each 10°C. The only temperature threshold which might exist would be at about 4°C.; there is no threshold at 20°C. as is postulated in the literature for anaerobic decomposition of sewage sludge.

Sludge bed behavior and conditions vary with time of the year and with river position. Bed properties vary with position in the Lower Fox River but are generally of the same order of magnitude. Appreciable differences in rate of decomposition occur at different river locations and at different times of the year in the same location.

The life of a fibrous sludge bed in the Lower Fox River would be one to two years if no new material were added to the bed. The amount of volatile solids destroyed by anaerobic decomposition in a year is approximately equal to the amount of volatile material which would be added to the river by the mills along its banks if the 1972 Wisconsin Department of Natural Resources water quality standards are met.

SUGGESTIONS FOR FURTHER WORK

This study has produced may ideas for further work in the area of anaerobic decomposition of fibrous systems, a relatively unexplored field.

The mathematical model for prediction of sludge bed distribution could be improved through refinement and further verification.

A kinetic model for anaerobic decomposition of cellulose could be developed which is closely tied to the qualitative model for the process here presented.

It might be feasible to utilize anaerobic decomposition as a waste treatment process for clarifier sludge, and this possibility should be investigated.

The bacterial dynamics of anaerobic decomposition would provide a fruitful area of study which would lead to a more thorough understanding of the process.

The effect of surface-to-volume ratio and of degree of lignification of the fibers on the rate of anaerobic decomposition could be investigated.

Further work is needed to establish with greater precision the critical nutrient levels required to sustain anaerobic decomposition of pulp fibers.

Finally, it would be most interesting to see if these results can be generalized to other river systems in other areas of the country or of the world which experience similar fibrous deposition.

SYMBOLS AND ABBREVIATIONS

abs. = absorbancy

$\underline{B}$ = bed constant in Velz equation

BOD = biological oxygen demand

$\underline{b}$ = 1/2-plate separation in free convection equation

$\underline{C}$ = average total solids content of sludge bed

COD = chemical oxygen demand

cal. = calorie

c.f.s. = cubic feet per second

concn. = concentration

$\underline{D}$, $\underline{d}$ = particle diameter

DNR = Wisconsin Department of Natural Resources

$\underline{d}_{tap}$ = distance between taps in permeability apparatus

FS = fixed solids

$\underline{f}$ = Weisback-Darcy friction factor

$\underline{g}$ = acceleration due to gravity

$\underline{H}$ = sludge depth, m.

$\underline{H}_{in}$ = sludge depth, in.

$\underline{h}_m$ = manometer reading

$\underline{K}$ = sludge permeability

kcal. = kilocalorie

$\underline{k}$ = Kozeny constant relating porosity and permeability

$\underline{k}_s$ = oxygen uptake rate

log = base 10 logarithm

ln = natural logarithm

$\underline{M}$ = molar

mc. = millicurie

$\underline{P}$ = pressure

p.p.m. = parts per million

p.s.i. = pounds per square inch

Re = Reynolds number

$\bar{\underline{r}}_i$ = average pore radius in sludge

$\underline{S}_o$ = specific surface area per unit volume

STP = standard temperature and pressure

$\underline{s}$ = specific gravity

std. = standard

$\underline{T}$ = bed life, years

$\underline{T}_d$ = bed life, days

TS = total solids

$\Delta\underline{T}$ = temperature difference

$\underline{t}$ = pad thickness in permeability apparatus

unk. = unknown

$\underline{V}$ = superficial velocity

$\underline{V}_c$ = mean channel velocity

$\underline{V}_o$ = void volume per unit volume

VS = volatile solids

$\underline{v}_{max}$ = maximum velocity

β = acute angle between slope of river bottom and the vertical

ε = sludge porosity

μ = viscosity of water

π = 3.1416

ρ = density

ξ = volume expansivity

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APPENDIX I

SOURCES OF WASTE DISCHARGE TO THE LOWER FOX RIVER

A profile of the Lower Fox River from Lake Winnebago to Green Bay is given in Fig. 34*. Figure 35 shows the locations of the various sources of waste discharge to the Lower Fox River. Table XXXV gives the specific locations of these discharges by section and the name of the source. These river sections are those defined in Table XVIII of the discussion (p. 58).

*This chart is reproduced from Chart 720 of the U.S. Lake Survey, Corps of Engineers, U.S. Army according to Form LS HO 6(12-70)(300) and is not to be used for navigational purposes.

LAKE WINNEBAGO AND LOWER FOX RIVER

WISCONSIN

POLYCONIC PROJECTION

NOTES
PLANES OF REFERENCE OF THIS CHART (Low Water Datum)
LAKE WINNEBAGO.................................745.1 ft.
FOX RIVER (Between Locks)..........................See table below
LAKE MICHIGAN.......................................576.8 ft.
Referred to mean water level at Father Point, Quebec, International Great Lakes Datum (1955).

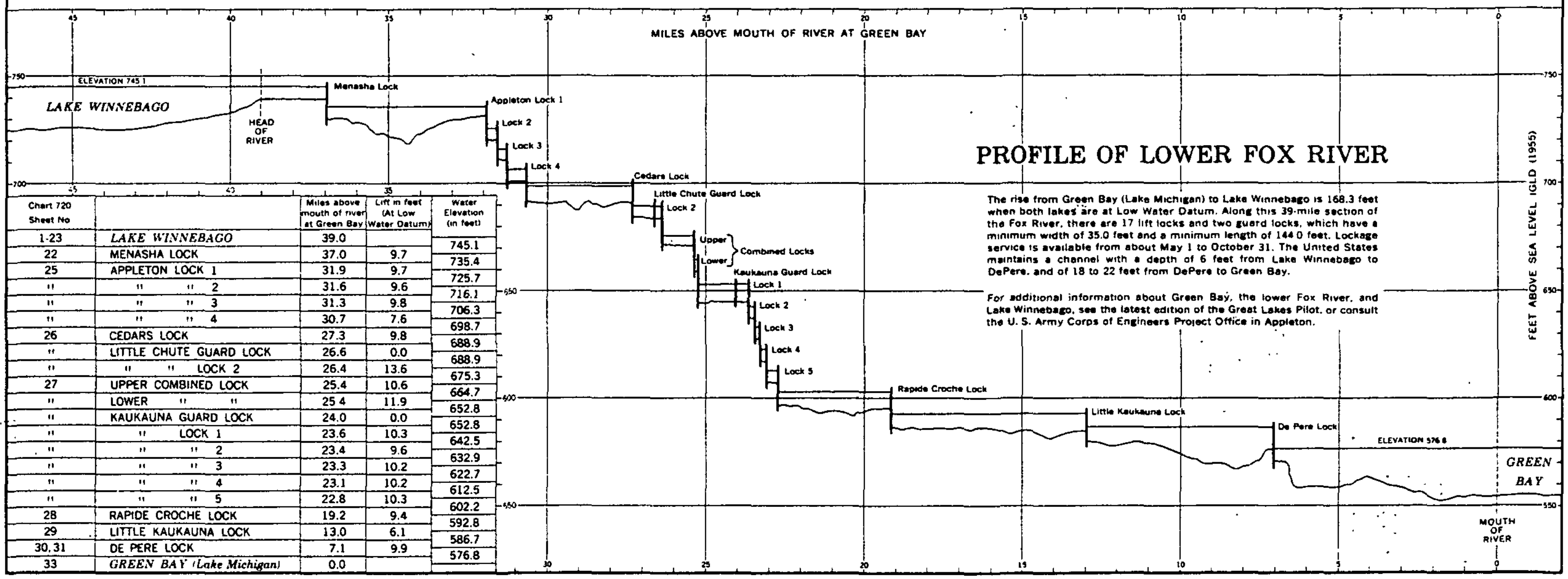

Chart 720 Sheet No		Miles above mouth of river at Green Bay	Lift in feet (At Low Water Datum)	Water Elevation (in feet)
1-23	*LAKE WINNEBAGO*	39.0		745.1
22	MENASHA LOCK	37.0	9.7	735.4
25	APPLETON LOCK 1	31.9	9.7	725.7
"	" " 2	31.6	9.6	716.1
"	" " 3	31.3	9.8	706.3
"	" " 4	30.7	7.6	698.7
26	CEDARS LOCK	27.3	9.8	688.9
"	LITTLE CHUTE GUARD LOCK	26.6	0.0	688.9
"	" " LOCK 2	26.4	13.6	675.3
27	UPPER COMBINED LOCK	25.4	10.6	664.7
"	LOWER " "	25.4	11.9	652.8
"	KAUKAUNA GUARD LOCK	24.0	0.0	652.8
"	" LOCK 1	23.6	10.3	642.5
"	" " 2	23.4	9.6	632.9
"	" " 3	23.3	10.2	622.7
"	" " 4	23.1	10.2	612.5
"	" " 5	22.8	10.3	602.2
28	RAPIDE CROCHE LOCK	19.2	9.4	592.8
29	LITTLE KAUKAUNA LOCK	13.0	6.1	586.7
30, 31	DE PERE LOCK	7.1	9.9	576.8
33	*GREEN BAY (Lake Michigan)*	0.0		

Figure 34

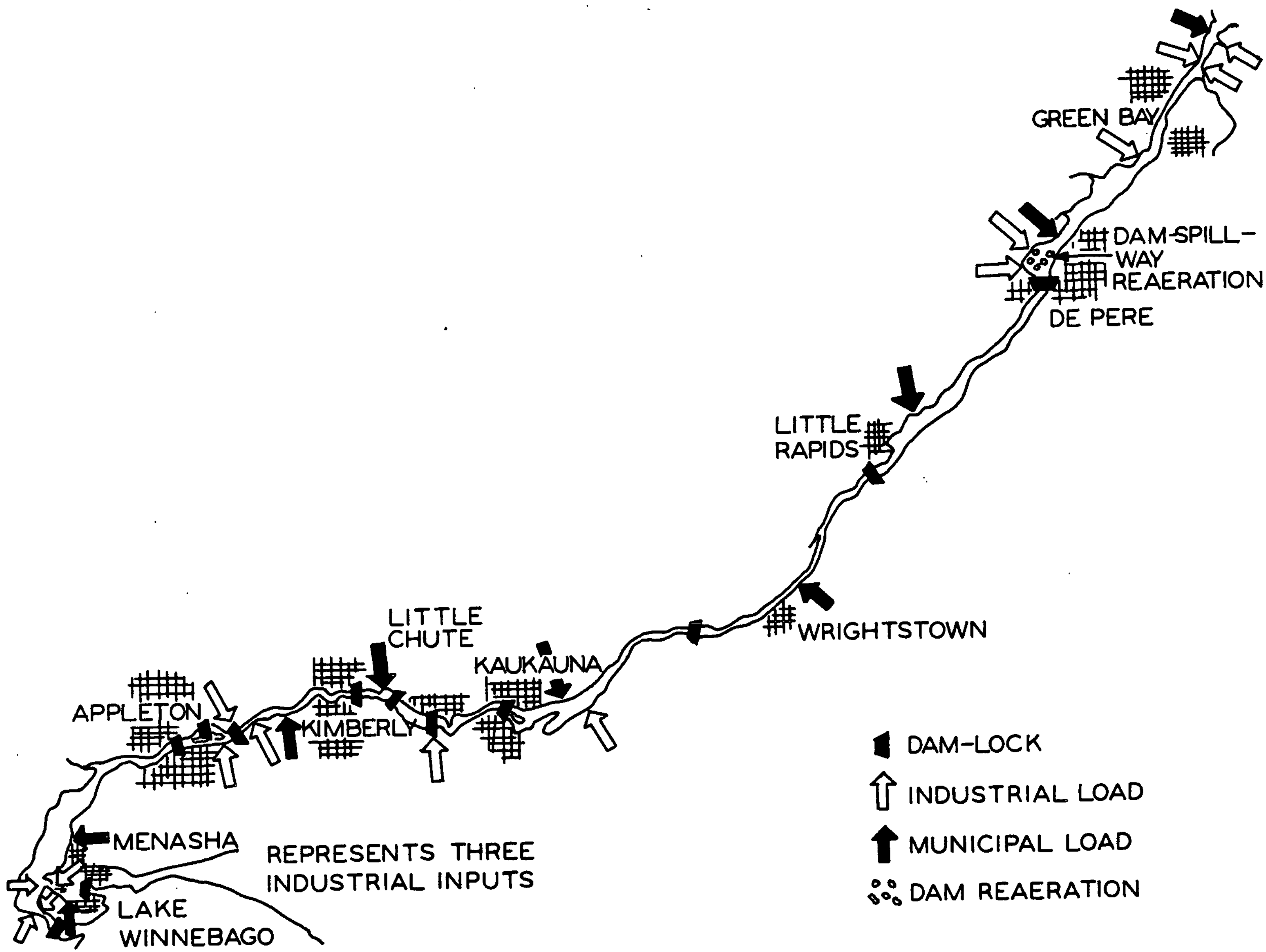

Figure 35. Lower Fox River — Lake Winnebago-Green Bay [Modified from (20)]

TABLE XXXV

SUMMARY OF WASTE DISCHARGES TO LOWER FOX RIVER
[Modified from (20)]

Section Number	Effluent Source
1	None
2	Kimberly-Clark Corp. (Neenah Paper), Kimberly-Clark Corp. (Badger Globe), and Bergstrom Paper Co.
3	Kimberly-Clark Corp. (Lakeview)
4	None
5	Gilbert Paper Co. and John Strange Paper Co.
6	Neenah-Menasha Sewage Treatment Plant
7	George A. Whiting Paper Co.
8	Town of Menasha Sewage Treatment Plant
9 to 13	None
14	Riverside Paper Co. and Foremost Foods
15	Consolidated Paper Co.
16	City of Appleton Sewage Treatment Plant
17	Kimberly-Clark Corp. (Kimberly mill) and Village of Kimberly Sewage Treatment Plant
18	Village of Little Chute Sewage Treatment Plant
19	None
20	Combined Papers, Inc.
21 to 23	None
24	City of Kaukauna Sewage Treatment Plant and Thilmany Pulp and Paper Company
25 to 26	None
27	Wrightstown Sewage Treatment Plant
28 to 30	None

TABLE XXXV (Continued)

SUMMARY OF WASTE DISCHARGES TO LOWER FOX RIVER
[Modified from (20)]

Section Number	Effluent Source
31	Hickory Grove Sanatorium
32	None
33	Nicolet Paper Co.
34	U.S. Paper Mills
35	City of DePere Sewage Treatment Plant
36 to 37	None
38	Fort Howard Paper Co. lagoons
39	Fort Howard Paper Co. white water
40 to 41	None
42	Charmin Paper Co.
43	Green Bay Packaging Co.
44	American Can Co. lagoon effluent
45	Green Bay Metropolitan Sewage Treatment Plant

APPENDIX II

MODEL FOR PREDICTING SLUDGE DISTRIBUTION

From the mineral deposit scour work (Tables VIII and IX, p. 21), the sewage sludge scour work, and knowledge of the composition of fibrous sludge beds, it seems reasonable to postulate that suspended fibers and clay would settle in the velocity range from 1 to 2 ft./sec., with the lower value more probable. The velocity at which deposits are scoured may be higher than that at which they will settle due to the structure in the deposit once it is formed.

Using the 1 and 2 ft./sec. critical velocity criteria, a computer model for sludge distribution in the Lower Fox River was developed. The model divides the river into 45 sections which are the same as those of the "Mathematical System Model of the Lower Fox River from Lake Winnebago to Green Bay" (20) prepared for the Wisconsin DNR; these sections are listed in Table XVIII (p. 58). A volume average velocity was computed for each section and compared to the criteria to determine whether or not sludge deposition should occur in the section. Velocities were computed based on different overall flow rates in the river as a whole. The model does not account for the true hydrodynamic flow pattern of the river but approximates it by the average in each section. The model does not compensate for the time required to scour a sludge deposit. Each section in the model is assumed to have a source of sludge input in it or input to it from the above section so that material is available for settling. This is not a bad assumption considering the abundance of sources on the Lower Fox River.

The program for performing these calculations is given in Table XXXVI. The nomenclature used is as follows:

CS = cross-sectional area of section

CFS = flow in $ft.^3/sec.$

CV = critical velocity

MONS = months

SV = section velocity

The average cross-sectional area of each section is given in Table XXXVII.

Application of the program to the maximum, minimum, and average flow conditions for 1969, 1970, and 1971 gave the results shown in Tables XXXVIII through XLIII. Application of the program to the monthly average flow rates for 1969, 1970, and 1971 gave the results shown in Tables XLIV through XLIX.

TABLE XXXVI

PROGRAM FOR SLUDGE DISTRIBUTION MODEL

```
/JOB GO,TIME=30
/FTC LIST
BPS FORTRAN D COMPILER
        C       BED DISTRIBUTION PROGRAM
                DIMENSION CS(50),CFS(50)
                READ(5,1) CV
                WRITE(6,1)CV
                DO 10 I=1,45
                READ(5,1)CS(I)
                WRITE(6,1)CS(I)
            1   FORMAT(F10.2)
           10   CONTINUE
                READ(5,2)MONS
                WRITE(6,2)MONS
            2   FORMAT(I2)
                DO 20 J=1,MONS
                READ(5,3) CFS(J)
                WRITE(6,3)CFS(J)
            3   FORMAT(F10.2)
           20   CONTINUE
                WRITE(6,11)
           11   FORMAT(1H1)
                DO 30 J=1,MONS
                WRITE(6,4)J,CFS(J)
           4    FORMAT(I4,5H CFS=,F10.2,/)
                DO 40 I=1,45
                SV=CFS(J)/CS(I)
                IF(SV-CV)41,41,42
           41   WRITE(6,5)I,SV
           5    FORMAT(I3,7H  YES  ,F10.3)
                GO TO 40
           42   WRITE(6,6)I,SV
            6   FORMAT(I3,7H   NO  ,F10.3)
           40   CONTINUE
                WRITE(6,7)
            7   FORMAT(1H1)
           30   CONTINUE
                STOP
                END
                  SIZE OF COMMON  00000    PROGRAM  01214
END OF COMPILATION  MAIN
```

TABLE XXXVII

AVERAGE CROSS-SECTIONAL AREA FOR
45 RIVER SECTIONS

Section Number	Area, $ft.^2$	Section Number	Area, $ft.^2$
1	978	24	6520
2	4000	25	4700
3	6950	26	2420
4	610	27	2920
5	712	28	4430
6	11600	29	5010
7	14600	30	8160
8	15100	31	10100
9	9820	32	9300
10	9990	33	4890
11	3670	34	10800
12	1670	35	8590
13	2000	36	11700
14	619	37	15100
15	3640	38	12000
16	4180	39	15000
17	2660	40	13000
18	4560	41	16100
19	6600	42	11900
20	1490	43	9930
21	3480	44	14000
22	290	45	12200
23	1470		

TABLE XXXVIII

DEPOSITION PREDICTIONS AT MAXIMUM, MINIMUM, AND AVERAGE FLOW RATES OF 1969

1 Ft./Sec. Flow Criterion

Maximum			Minimum			Average		
1 CFS=	16120.00		2 CFS=	870.00		3 CFS=	4807.00	
1[a]	NO[b]	16.483[c]	1[a]	YES[b]	0.890[c]	1[a]	NO[b]	4.915[c]
2	NO	4.030	2	YES	0.217	2	NO	1.202
3	NO	2.319	3	YES	0.125	3	YES	0.692
4	NO	26.426	4	NO	1.426	4	NO	7.880
5	NO	22.640	5	NO	1.222	5	NO	6.751
6	NO	1.390	6	YES	0.075	6	YES	0.414
7	NO	1.104	7	YES	0.060	7	YES	0.329
8	NO	1.068	8	YES	0.058	8	YES	0.318
9	NO	1.642	9	YES	0.089	9	YES	0.490
10	NO	1.614	10	YES	0.087	10	YES	0.481
11	NO	4.392	11	YES	0.237	11	NO	1.310
12	NO	9.653	12	YES	0.521	12	NO	2.878
13	NO	8.060	13	YES	0.435	13	NO	2.403
14	NO	26.042	14	NO	1.405	14	NO	7.766
15	NO	4.429	15	YES	0.239	15	NO	1.321
16	NO	3.856	16	YES	0.208	16	NO	1.150
17	NO	6.060	17	YES	0.327	17	NO	1.807
18	NO	3.535	18	YES	0.191	18	NO	1.054
19	NO	2.442	19	YES	0.132	19	YES	0.728
20	NO	10.819	20	YES	0.584	20	NO	3.226
21	NO	4.632	21	YES	0.250	21	NO	1.381
22	NO	55.586	22	NO	3.000	22	NO	16.576
23	NO	10.966	23	YES	0.592	23	NO	3.270
24	NO	2.472	24	YES	0.133	24	YES	0.737
25	NO	3.430	25	YES	0.185	25	NO	1.023
26	NO	6.661	26	YES	0.360	26	NO	1.986
27	NO	5.521	27	YES	0.298	27	NO	1.646
28	NO	3.639	28	YES	0.196	28	NO	1.085
29	NO	3.218	29	YES	0.174	29	YES	0.959
30	NO	1.975	30	YES	0.107	30	YES	0.589
31	NO	1.596	31	YES	0.086	31	YES	0.476
32	NO	1.733	32	YES	0.094	32	YES	0.517
33	NO	3.297	33	YES	0.178	33	YES	0.983
34	NO	1.493	34	YES	0.081	34	YES	0.445
35	NO	1.877	35	YES	0.101	35	YES	0.560
36	NO	1.378	36	YES	0.074	36	YES	0.411
37	NO	1.068	37	YES	0.058	37	YES	0.318
38	NO	1.343	38	YES	0.072	38	YES	0.401
39	NO	1.075	39	YES	0.058	39	YES	0.320
40	NO	1.240	40	YES	0.067	40	YES	0.370
41	NO	1.001	41	YES	0.054	41	YES	0.299
42	NO	1.355	42	YES	0.073	42	YES	0.404
43	NO	1.623	43	YES	0.088	43	YES	0.484
44	NO	1.151	44	YES	0.062	44	YES	0.343
45	NO	1.321	45	YES	0.071	45	YES	0.394

[a]River section.

[b]Deposition predicted?

[c]Average flow velocity through section, ft./sec.

TABLE XXXIX

DEPOSITION PREDICTIONS AT MAXIMUM, MINIMUM, AND AVERAGE FLOW RATES OF 1969

2 Ft./Sec. Flow Criterion

Maximum			Minimum			Average		
1 CFS=		16120.00	2 CFS=		870.00	3 CFS=		4807.00
1	NO	16.483	1	YES	0.890	1	NO	4.915
2	NO	4.030	2	YES	0.217	2	YES	1.202
3	NO	2.319	3	YES	0.125	3	YES	0.692
4	NO	26.426	4	YES	1.426	4	NO	7.880
5	NO	22.640	5	YES	1.222	5	NO	6.751
6	YES	1.390	6	YES	0.075	6	YES	0.414
7	YES	1.104	7	YES	0.060	7	YES	0.329
8	YES	1.068	8	YES	0.058	8	YES	0.318
9	YES	1.642	9	YES	0.089	9	YES	0.490
10	YES	1.614	10	YES	0.087	10	YES	0.481
11	NO	4.392	11	YES	0.237	11	YES	1.310
12	NO	9.653	12	YES	0.521	12	NO	2.878
13	NO	8.060	13	YES	0.435	13	NO	2.403
14	NO	26.042	14	YES	1.405	14	NO	7.766
15	NO	4.429	15	YES	0.239	15	YES	1.321
16	NO	3.856	16	YES	0.208	16	YES	1.150
17	NO	6.060	17	YES	0.327	17	YES	1.807
18	NO	3.535	18	YES	0.191	18	YES	1.054
19	NO	2.442	19	YES	0.132	19	YES	0.728
20	NO	10.819	20	YES	0.584	20	NO	3.226
21	NO	4.632	21	YES	0.250	21	YES	1.381
22	NO	55.586	22	NO	3.000	22	NO	16.576
23	NO	10.966	23	YES	0.592	23	NO	3.270
24	NO	2.472	24	YES	0.133	24	YES	0.737
25	NO	3.430	25	YES	0.185	25	YES	1.023
26	NO	6.661	26	YES	0.360	26	YES	1.986
27	NO	5.521	27	YES	0.298	27	YES	1.646
28	NO	3.639	28	YES	0.196	28	YES	1.085
29	NO	3.218	29	YES	0.174	29	YES	0.959
30	YES	1.975	30	YES	0.107	30	YES	0.589
31	YES	1.596	31	YES	0.086	31	YES	0.476
32	YES	1.733	32	YES	0.094	32	YES	0.517
33	NO	3.297	33	YES	0.178	33	YES	0.983
34	YES	1.493	34	YES	0.081	34	YES	0.445
35	YES	1.877	35	YES	0.101	35	YES	0.560
36	YES	1.378	36	YES	0.074	36	YES	0.411
37	YES	1.068	37	YES	0.058	37	YES	0.318
38	YES	1.343	38	YES	0.072	38	YES	0.401
39	YES	1.075	39	YES	0.058	39	YES	0.320
40	YES	1.240	40	YES	0.067	40	YES	0.370
41	YES	1.001	41	YES	0.054	41	YES	0.299
42	YES	1.355	42	YES	0.073	42	YES	0.404
43	YES	1.623	43	YES	0.088	43	YES	0.484
44	YES	1.151	44	YES	0.062	44	YES	0.343
45	YES	1.321	45	YES	0.071	45	YES	0.394

TABLE XL

DEPOSITION PREDICTIONS AT MAXIMUM, MINIMUM, AND AVERAGE FLOW RATES OF 1970

1 Ft./Sec. Flow Criterion

Maximum			Minimum			Average		
1 CFS=		12160.00	2 CFS=		760.00	3 CFS=		3239.00
1	NO	12.434	1	YES	0.777	1	NO	3.312
2	NO	3.040	2	YES	0.190	2	YES	0.810
3	NO	1.750	3	YES	0.109	3	YES	0.466
4	NO	19.934	4	NO	1.246	4	NO	5.310
5	NO	17.079	5	NO	1.067	5	NO	4.549
6	NO	1.048	6	YES	0.066	6	YES	0.279
7	YES	0.833	7	YES	0.052	7	YES	0.222
8	YES	0.805	8	YES	0.050	8	YES	0.215
9	NO	1.238	9	YES	0.077	9	YES	0.330
10	NO	1.217	10	YES	0.076	10	YES	0.324
11	NO	3.313	11	YES	0.207	11	YES	0.883
12	NO	7.281	12	YES	0.455	12	NO	1.940
13	NO	6.080	13	YES	0.380	13	NO	1.619
14	NO	19.645	14	NO	1.228	14	NO	5.233
15	NO	3.341	15	YES	0.209	15	YES	0.890
16	NO	2.909	16	YES	0.182	16	YES	0.775
17	NO	4.571	17	YES	0.286	17	NO	1.218
18	NO	2.667	18	YES	0.167	18	YES	0.710
19	NO	1.842	19	YES	0.115	19	YES	0.491
20	NO	8.161	20	YES	0.510	20	NO	2.174
21	NO	3.494	21	YES	0.218	21	YES	0.931
22	NO	41.931	22	NO	2.621	22	NO	11.169
23	NO	8.272	23	YES	0.517	23	NO	2.203
24	NO	1.865	24	YES	0.117	24	YES	0.497
25	NO	2.587	25	YES	0.162	25	YES	0.689
26	NO	5.025	26	YES	0.314	26	NO	1.338
27	NO	4.164	27	YES	0.260	27	NO	1.109
28	NO	2.745	28	YES	0.172	28	YES	0.731
29	NO	2.427	29	YES	0.152	29	YES	0.647
30	NO	1.490	30	YES	0.093	30	YES	0.397
31	NO	1.204	31	YES	0.075	31	YES	0.321
32	NO	1.308	32	YES	0.082	32	YES	0.348
33	NO	2.487	33	YES	0.155	33	YES	0.662
34	NO	1.126	34	YES	0.070	34	YES	0.300
35	NO	1.416	35	YES	0.088	35	YES	0.377
36	NO	1.039	36	YES	0.065	36	YES	0.277
37	YES	0.805	37	YES	0.050	37	YES	0.215
38	NO	1.013	38	YES	0.063	38	YES	0.270
39	YES	0.811	39	YES	0.051	39	YES	0.216
40	YES	0.935	40	YES	0.058	40	YES	0.249
41	YES	0.755	41	YES	0.047	41	YES	0.201
42	NO	1.022	42	YES	0.064	42	YES	0.272
43	NO	1.225	43	YES	0.077	43	YES	0.326
44	YES	0.869	44	YES	0.054	44	YES	0.231
45	YES	0.997	45	YES	0.062	45	YES	0.265

TABLE XLI

DEPOSITION PREDICTIONS AT MAXIMUM, MINIMUM, AND AVERAGE FLOW RATES OF 1970

2 Ft./Sec. Flow Criterion

	Maximum			Minimum			Average	
	1 CFS=	12160.00		2 CFS=	760.00		3 CFS=	3239.00
1	NO	12.434	1	YES	0.777	1	NO	3.312
2	NO	3.040	2	YES	0.190	2	YES	0.810
3	YES	1.750	3	YES	0.109	3	YES	0.466
4	NO	19.934	4	YES	1.246	4	NO	5.310
5	NO	17.079	5	YES	1.067	5	NO	4.549
6	YES	1.048	6	YES	0.066	6	YES	0.279
7	YES	0.833	7	YES	0.052	7	YES	0.222
8	YES	0.805	8	YES	0.050	8	YES	0.215
9	YES	1.238	9	YES	0.077	9	YES	0.330
10	YES	1.217	10	YES	0.076	10	YES	0.324
11	NO	3.313	11	YES	0.207	11	YES	0.883
12	NO	7.281	12	YES	0.455	12	YES	1.940
13	NO	6.080	13	YES	0.380	13	YES	1.619
14	NO	19.645	14	YES	1.228	14	NO	5.233
15	NO	3.341	15	YES	0.209	15	YES	0.890
16	NO	2.909	16	YES	0.182	16	YES	0.775
17	NO	4.571	17	YES	0.286	17	YES	1.218
18	NO	2.667	18	YES	0.167	18	YES	0.710
19	YES	1.842	19	YES	0.115	19	YES	0.491
20	NO	8.161	20	YES	0.510	20	NO	2.174
21	NO	3.494	21	YES	0.218	21	YES	0.931
22	NO	41.931	22	NO	2.621	22	NO	11.169
23	NO	8.272	23	YES	0.517	23	NO	2.203
24	YES	1.865	24	YES	0.117	24	YES	0.497
25	NO	2.587	25	YES	0.162	25	YES	0.689
26	NO	5.025	26	YES	0.314	26	YES	1.338
27	NO	4.164	27	YES	0.260	27	YES	1.109
28	NO	2.745	28	YES	0.172	28	YES	0.731
29	NO	2.427	29	YES	0.152	29	YES	0.647
30	YES	1.490	30	YES	0.093	30	YES	0.397
31	YES	1.204	31	YES	0.075	31	YES	0.321
32	YES	1.308	32	YES	0.082	32	YES	0.348
33	NO	2.487	33	YES	0.155	33	YES	0.662
34	YES	1.126	34	YES	0.070	34	YES	0.300
35	YES	1.416	35	YES	0.088	35	YES	0.377
36	YES	1.039	36	YES	0.065	36	YES	0.277
37	YES	0.805	37	YES	0.050	37	YES	0.215
38	YES	1.013	38	YES	0.063	38	YES	0.270
39	YES	0.811	39	YES	0.051	39	YES	0.216
40	YES	0.935	40	YES	0.058	40	YES	0.249
41	YES	0.755	41	YES	0.047	41	YES	0.201
42	YES	1.022	42	YES	0.064	42	YES	0.272
43	YES	1.225	43	YES	0.077	43	YES	0.326
44	YES	0.869	44	YES	0.054	44	YES	0.231
45	YES	0.997	45	YES	0.062	45	YES	0.265

TABLE XLII

DEPOSITION PREDICTIONS AT MAXIMUM, MINIMUM,
AND AVERAGE FLOW RATES OF 1971

1 Ft./Sec. Flow Criterion

Maximum			Minimum			Average		
1 CFS=		10790.00	2 CFS=		1282.00	3 CFS=		3934.00
1	NO	11.033	1	NO	1.311	1	NO	4.022
2	NO	2.697	2	YES	0.320	2	YES	0.983
3	NO	1.553	3	YES	0.184	3	YES	0.566
4	NO	17.689	4	NO	2.102	4	NO	6.449
5	NO	15.154	5	NO	1.801	5	NO	5.525
6	YES	0.930	6	YES	0.111	6	YES	0.339
7	YES	0.739	7	YES	0.088	7	YES	0.269
8	YES	0.715	8	YES	0.085	8	YES	0.261
9	NO	1.099	9	YES	0.131	9	YES	0.401
10	NO	1.080	10	YES	0.128	10	YES	0.394
11	NO	2.940	11	YES	0.349	11	NO	1.072
12	NO	6.461	12	YES	0.768	12	NO	2.356
13	NO	5.395	13	YES	0.641	13	NO	1.967
14	NO	17.431	14	NO	2.071	14	NO	6.355
15	NO	2.964	15	YES	0.352	15	NO	1.081
16	NO	2.581	16	YES	0.307	16	YES	0.941
17	NO	4.056	17	YES	0.482	17	NO	1.479
18	NO	2.366	18	YES	0.281	18	YES	0.863
19	NO	1.635	19	YES	0.194	19	YES	0.596
20	NO	7.242	20	YES	0.860	20	NO	2.640
21	NO	3.101	21	YES	0.368	21	NO	1.130
22	NO	37.207	22	NO	4.421	22	NO	13.566
23	NO	7.340	23	YES	0.872	23	NO	2.676
24	NO	1.655	24	YES	0.197	24	YES	0.603
25	NO	2.296	25	YES	0.273	25	YES	0.837
26	NO	4.459	26	YES	0.530	26	NO	1.626
27	NO	3.695	27	YES	0.439	27	NO	1.347
28	NO	2.436	28	YES	0.289	28	YES	0.888
29	NO	2.154	29	YES	0.256	29	YES	0.785
30	NO	1.322	30	YES	0.157	30	YES	0.482
31	NO	1.068	31	YES	0.127	31	YES	0.390
32	NO	1.160	32	YES	0.138	32	YES	0.423
33	NO	2.207	33	YES	0.262	33	YES	0.804
34	YES	0.999	34	YES	0.119	34	YES	0.364
35	NO	1.256	35	YES	0.149	35	YES	0.458
36	YES	0.922	36	YES	0.110	36	YES	0.336
37	YES	0.715	37	YES	0.085	37	YES	0.261
38	YES	0.899	38	YES	0.107	38	YES	0.328
39	YES	0.719	39	YES	0.085	39	YES	0.262
40	YES	0.830	40	YES	0.099	40	YES	0.303
41	YES	0.670	41	YES	0.080	41	YES	0.244
42	YES	0.907	42	YES	0.108	42	YES	0.331
43	NO	1.087	43	YES	0.129	43	YES	0.396
44	YES	0.771	44	YES	0.092	44	YES	0.281
45	YES	0.884	45	YES	0.105	45	YES	0.322

TABLE XLIII

DEPOSITION PREDICTIONS AT MAXIMUM, MINIMUM,
AND AVERAGE FLOW RATES OF 1971

2 Ft./Sec. Flow Criterion

Maximum			Minimum			Average		
1 CFS=		10790.00	2 CFS=		1282.00	3 CFS=		3934.00
1	NO	11.033	1	YES	1.311	1	NO	4.022
2	NO	2.697	2	YES	0.320	2	YES	0.983
3	YES	1.553	3	YES	0.184	3	YES	0.566
4	NO	17.689	4	NO	2.102	4	NO	6.449
5	NO	15.154	5	YES	1.801	5	NO	5.525
6	YES	0.930	6	YES	0.111	6	YES	0.339
7	YES	0.739	7	YES	0.088	7	YES	0.269
8	YES	0.715	8	YES	0.085	8	YES	0.261
9	YES	1.099	9	YES	0.131	9	YES	0.401
10	YES	1.080	10	YES	0.128	10	YES	0.394
11	NO	2.940	11	YES	0.349	11	YES	1.072
12	NO	6.461	12	YES	0.768	12	NO	2.356
13	NO	5.395	13	YES	0.641	13	YES	1.967
14	NO	17.431	14	NO	2.071	14	NO	6.355
15	NO	2.964	15	YES	0.352	15	YES	1.081
16	NO	2.581	16	YES	0.307	16	YES	0.941
17	NO	4.056	17	YES	0.482	17	YES	1.479
18	NO	2.366	18	YES	0.281	18	YES	0.863
19	YES	1.635	19	YES	0.194	19	YES	0.596
20	NO	7.242	20	YES	0.860	20	NO	2.640
21	NO	3.101	21	YES	0.368	21	YES	1.130
22	NO	37.207	22	NO	4.421	22	NO	13.566
23	NO	7.340	23	YES	0.872	23	NO	2.676
24	YES	1.655	24	YES	0.197	24	YES	0.603
25	NO	2.296	25	YES	0.273	25	YES	0.837
26	NO	4.459	26	YES	0.530	26	YES	1.626
27	NO	3.695	27	YES	0.439	27	YES	1.347
28	NO	2.436	28	YES	0.289	28	YES	0.888
29	NO	2.154	29	YES	0.256	29	YES	0.785
30	YES	1.322	30	YES	0.157	30	YES	0.482
31	YES	1.068	31	YES	0.127	31	YES	0.390
32	YES	1.160	32	YES	0.138	32	YES	0.423
33	NO	2.207	33	YES	0.262	33	YES	0.804
34	YES	0.999	34	YES	0.119	34	YES	0.364
35	YES	1.256	35	YES	0.149	35	YES	0.458
36	YES	0.922	36	YES	0.110	36	YES	0.336
37	YES	0.715	37	YES	0.085	37	YES	0.261
38	YES	0.899	38	YES	0.107	38	YES	0.328
39	YES	0.719	39	YES	0.085	39	YES	0.262
40	YES	0.830	40	YES	0.099	40	YES	0.303
41	YES	0.670	41	YES	0.080	41	YES	0.244
42	YES	0.907	42	YES	0.108	42	YES	0.331
43	YES	1.087	43	YES	0.129	43	YES	0.396
44	YES	0.771	44	YES	0.092	44	YES	0.281
45	YES	0.884	45	YES	0.105	45	YES	0.322

TABLE XLIV

DEPOSITION PREDICTIONS FOR MONTHLY AVERAGE
FLOW RATES OF 1969

1 Ft./Sec. Flow Criterion

January			February			March			April			May			June		
1 CFS = 4842.00			2 CFS = 5667.00			3 CFS = 4545.00			4 CFS = 9055.00			5 CFS = 6136.00			6 CFS = 4764.00		
1	No	4.951	1	No	5.794	1	No	4.647	1	No	9.259	1	No	6.274	1	No	4.871
2	No	1.210	2	No	1.417	2	No	1.136	2	No	2.264	2	No	1.534	2	No	1.191
3	Yes	0.697	3	Yes	0.815	3	Yes	0.654	3	No	1.303	3	Yes	0.883	3	Yes	0.685
4	No	7.938	4	No	9.290	4	No	7.451	4	No	14.844	4	No	10.059	4	No	7.810
5	No	6.801	5	No	7.959	5	No	6.383	5	No	12.718	5	No	8.618	5	No	6.691
6	Yes	0.417	6	Yes	0.489	6	Yes	0.392	6	Yes	0.781	6	Yes	0.529	6	Yes	0.411
7	Yes	0.332	7	Yes	0.388	7	Yes	0.311	7	Yes	0.620	7	Yes	0.420	7	Yes	0.326
8	Yes	0.321	8	Yes	0.375	8	Yes	0.301	8	Yes	0.600	8	Yes	0.406	8	Yes	0.315
9	Yes	0.493	9	Yes	0.577	9	Yes	0.463	9	Yes	0.922	9	Yes	0.625	9	Yes	0.485
10	Yes	0.485	10	Yes	0.567	10	Yes	0.455	10	Yes	0.906	10	Yes	0.614	10	Yes	0.477
11	No	1.319	11	No	1.544	11	No	1.238	11	No	2.467	11	No	1.672	11	No	1.298
12	No	2.899	12	No	3.393	12	No	2.722	12	No	5.422	12	No	3.674	12	No	2.853
13	No	2.421	13	No	2.833	13	No	2.272	13	No	4.527	13	No	3.068	13	No	2.382
14	No	7.822	14	No	9.155	14	No	7.342	14	No	4.628	14	No	9.913	14	No	7.696
15	No	1.330	15	No	1.557	15	No	1.249	15	No	2.488	15	No	1.686	15	No	1.309
16	No	1.158	16	No	1.356	16	No	1.087	16	No	2.166	16	No	1.468	16	No	1.140
17	No	1.820	17	No	2.130	17	No	1.709	17	No	3.404	17	No	2.307	17	No	1.791
18	No	1.062	18	No	1.243	18	Yes	0.997	18	No	1.986	18	No	1.346	18	No	1.045
19	Yes	0.734	19	Yes	0.859	19	Yes	0.689	19	No	1.372	19	Yes	0.930	19	Yes	0.722
20	No	3.250	20	No	3.803	20	No	3.050	20	No	6.077	20	No	4.118	20	No	3.197
21	No	1.391	21	No	1.628	21	No	1.306	21	No	2.602	21	No	1.763	21	No	1.369
22	No	16.697	22	No	19.541	22	No	15.672	22	No	31.224	22	No	21.159	22	No	16.428
23	No	3.294	23	No	3.855	23	No	3.092	23	No	6.160	23	No	4.174	23	No	3.241
24	Yes	0.743	24	Yes	0.869	24	Yes	0.697	24	No	1.389	24	Yes	0.941	24	Yes	0.731
25	No	1.030	25	No	1.206	25	Yes	0.967	25	No	1.927	25	No	1.306	25	No	1.014
26	No	2.001	26	No	2.342	26	No	1.878	26	No	3.742	26	No	2.536	26	No	1.969
27	No	1.658	27	No	1.941	27	No	1.557	27	No	3.101	27	No	2.101	27	No	1.632
28	No	1.093	28	No	1.279	28	No	1.026	28	No	2.044	28	No	1.385	28	No	1.075
29	Yes	0.966	29	No	1.131	29	Yes	0.907	29	No	1.807	29	No	1.225	29	Yes	0.951
30	Yes	0.593	30	Yes	0.694	30	Yes	0.557	30	No	1.110	30	Yes	0.752	30	Yes	0.584
31	Yes	0.479	31	Yes	0.561	31	Yes	0.450	31	Yes	0.897	31	Yes	0.608	31	Yes	0.472
32	Yes	0.521	32	Yes	0.609	32	Yes	0.489	32	Yes	0.974	32	Yes	0.660	32	Yes	0.512
33	Yes	0.990	33	No	1.159	33	Yes	0.929	33	No	1.852	33	No	1.255	33	Yes	0.974
34	Yes	0.448	34	Yes	0.525	34	Yes	0.421	34	Yes	0.838	34	Yes	0.568	34	Yes	0.441
35	Yes	0.564	35	Yes	0.660	35	Yes	0.529	35	No	1.054	35	Yes	0.714	35	Yes	0.555
36	Yes	0.414	36	Yes	0.484	36	Yes	0.388	36	Yes	0.774	36	Yes	0.524	36	Yes	0.407
37	Yes	0.321	37	Yes	0.375	37	Yes	0.301	37	Yes	0.600	37	Yes	0.406	37	Yes	0.315
38	Yes	0.403	38	Yes	0.472	38	Yes	0.379	38	Yes	0.755	38	Yes	0.511	38	Yes	0.397
39	Yes	0.323	39	Yes	0.378	39	Yes	0.303	39	Yes	0.604	39	Yes	0.409	39	Yes	0.318
40	Yes	0.372	40	Yes	0.436	40	Yes	0.350	40	Yes	0.697	40	Yes	0.472	40	Yes	0.366
41	Yes	0.301	41	Yes	0.352	41	Yes	0.282	41	Yes	0.562	41	Yes	0.381	41	Yes	0.296
42	Yes	0.407	42	Yes	0.476	42	Yes	0.382	42	Yes	0.761	42	Yes	0.516	42	Yes	0.400
43	Yes	0.488	43	Yes	0.571	43	Yes	0.458	43	Yes	0.912	43	Yes	0.618	43	Yes	0.480
44	Yes	0.346	44	Yes	0.405	44	Yes	0.325	44	Yes	0.647	44	Yes	0.438	44	Yes	0.340
45	Yes	0.397	45	Yes	0.465	45	Yes	0.373	45	Yes	0.742	45	Yes	0.503	45	Yes	0.390

TABLE XLIV (Continued)

DEPOSITION PREDICTIONS FOR MONTHLY AVERAGE FLOW RATES OF 1969

1 Ft./Sec. Flow Criterion

July			August			September			October			November			December		
7 CFS = 11154.00			8 CFS = 2250.00			9 CFS = 1472.00			10 CFS = 1745.00			11 CFS = 2974.00			12 CFS = 3129.00		
1	No	11.405	1	No	2.301	1	No	1.505	1	No	1.784	1	No	3.041	1	No	3.199
2	No	2.788	2	Yes	0.563	2	Yes	0.368	2	Yes	0.436	2	Yes	0.743	2	Yes	0.782
3	No	1.605	3	Yes	0.324	3	Yes	0.212	3	Yes	0.251	3	Yes	0.428	3	Yes	0.450
4	No	18.285	4	No	3.689	4	No	2.413	4	No	2.861	4	No	4.875	4	No	5.130
5	No	15.666	5	No	3.160	5	No	2.067	5	No	2.451	5	No	4.177	5	No	4.395
6	Yes	0.962	6	Yes	0.194	6	Yes	0.127	6	Yes	0.150	6	Yes	0.256	6	Yes	0.270
7	Yes	0.764	7	Yes	0.154	7	Yes	0.101	7	Yes	0.120	7	Yes	0.204	7	Yes	0.214
8	Yes	0.739	8	Yes	0.149	8	Yes	0.097	8	Yes	0.116	8	Yes	0.197	8	Yes	0.207
9	No	1.136	9	Yes	0.229	9	Yes	0.150	9	Yes	0.178	9	Yes	0.303	9	Yes	0.319
10	No	1.117	10	Yes	0.225	10	Yes	0.147	10	Yes	0.175	10	Yes	0.298	10	Yes	0.313
11	No	3.039	11	Yes	0.613	11	Yes	0.401	11	Yes	0.475	11	Yes	0.810	11	Yes	0.853
12	No	6.679	12	No	1.347	12	Yes	0.881	12	No	1.045	12	No	1.781	12	No	1.874
13	No	5.577	13	No	1.125	13	Yes	0.736	13	Yes	0.872	13	No	1.487	13	No	1.564
14	No	8.019	14	No	3.635	14	No	2.378	14	No	2.819	14	No	4.805	14	No	5.055
15	No	3.064	15	Yes	0.618	15	Yes	0.404	15	Yes	0.479	15	Yes	0.817	15	Yes	0.860
16	No	2.668	16	Yes	0.538	16	Yes	0.352	16	Yes	0.417	16	Yes	0.711	16	Yes	0.749
17	No	4.193	17	Yes	0.846	17	Yes	0.553	17	Yes	0.656	17	No	1.118	17	No	1.176
18	No	2.446	18	Yes	0.493	18	Yes	0.323	18	Yes	0.383	18	Yes	0.652	18	Yes	0.686
19	No	1.690	19	Yes	0.341	19	Yes	0.223	19	Yes	0.264	19	Yes	0.451	19	Yes	0.474
20	No	7.486	20	No	1.510	20	Yes	0.988	20	No	1.171	20	No	1.996	20	No	2.100
21	No	3.205	21	Yes	0.647	21	Yes	0.423	21	Yes	0.501	21	Yes	0.855	21	Yes	0.899
22	No	8.462	22	No	7.759	22	No	5.076	22	No	6.017	22	No	10.255	22	No	0.790
23	No	7.588	23	No	1.531	23	No	1.001	23	No	1.187	23	No	2.023	23	No	2.129
24	No	1.711	24	Yes	0.345	24	Yes	0.226	24	Yes	0.268	24	Yes	0.456	24	Yes	0.480
25	No	2.373	25	Yes	0.479	25	Yes	0.313	25	Yes	0.371	25	Yes	0.633	25	Yes	0.666
26	No	4.609	26	Yes	0.930	26	Yes	0.608	26	Yes	0.721	26	No	1.229	26	No	1.293
27	No	3.820	27	Yes	0.771	27	Yes	0.504	27	Yes	0.598	27	No	1.018	27	No	1.072
28	No	2.518	28	Yes	0.508	28	Yes	0.332	28	Yes	0.394	28	Yes	0.671	28	Yes	0.706
29	No	2.226	29	Yes	0.449	29	Yes	0.294	29	Yes	0.348	29	Yes	0.594	29	Yes	0.625
30	No	1.367	30	Yes	0.276	30	Yes	0.180	30	Yes	0.214	30	Yes	0.364	30	Yes	0.383
31	No	1.104	31	Yes	0.223	31	Yes	0.146	31	Yes	0.173	31	Yes	0.294	31	Yes	0.310
32	No	1.199	32	Yes	0.242	32	Yes	0.158	32	Yes	0.188	32	Yes	0.320	32	Yes	0.336
33	No	2.281	33	Yes	0.460	33	Yes	0.301	33	Yes	0.357	33	Yes	0.608	33	Yes	0.640
34	No	1.033	34	Yes	0.208	34	Yes	0.136	34	Yes	0.162	34	Yes	0.275	34	Yes	0.290
35	No	1.298	35	Yes	0.262	35	Yes	0.171	35	Yes	0.203	35	Yes	0.346	35	Yes	0.364
36	Yes	0.953	36	Yes	0.192	36	Yes	0.126	36	Yes	0.149	36	Yes	0.254	36	Yes	0.267
37	Yes	0.739	37	Yes	0.149	37	Yes	0.097	37	Yes	0.116	37	Yes	0.197	37	Yes	0.207
38	Yes	0.929	38	Yes	0.188	38	Yes	0.123	38	Yes	0.145	38	Yes	0.248	38	Yes	0.261
39	Yes	0.744	39	Yes	0.150	39	Yes	0.098	39	Yes	0.116	39	Yes	0.198	39	Yes	0.209
40	Yes	0.858	40	Yes	0.173	40	Yes	0.113	40	Yes	0.134	40	Yes	0.229	40	Yes	0.241
41	Yes	0.693	41	Yes	0.140	41	Yes	0.091	41	Yes	0.108	41	Yes	0.185	41	Yes	0.194
42	Yes	0.937	42	Yes	0.189	42	Yes	0.124	42	Yes	0.147	42	Yes	0.250	42	Yes	0.263
43	No	1.123	43	Yes	0.227	43	Yes	0.148	43	Yes	0.176	43	Yes	0.299	43	Yes	0.315
44	Yes	0.797	44	Yes	0.161	44	Yes	0.105	44	Yes	0.125	44	Yes	0.212	44	Yes	0.223
45	Yes	0.914	45	Yes	0.184	45	Yes	0.121	45	Yes	0.143	45	Yes	0.244	45	Yes	0.256

TABLE XLV

DEPOSITION PREDICTIONS FOR MONTHLY AVERAGE FLOW RATES OF 1969

2 Ft./Sec. Flow Criterion

	January		February		March		April		May		June	
	1 CFS=	4842.00	2 CFS=	5667.00	3 CFS=	4545.00	4 CFS=	9055.00	5 CFS=	6136.00	6 CFS=	4764.00
1	NO	4.951	NO	5.794	NO	4.647	NO	9.259	NO	6.274	NO	4.871
2	YES	1.210	YES	1.417	YES	1.136	NO	2.264	YES	1.534	YES	1.191
3	YES	0.697	YES	0.815	YES	0.654	YES	1.303	YES	0.883	YES	0.685
4	NO	7.938	NO	9.290	NO	7.451	NO	14.844	NO	10.059	NO	7.810
5	NO	6.801	NO	7.959	NO	6.383	NO	12.718	NO	8.618	NO	6.691
6	YES	0.417	YES	0.489	YES	0.392	YES	0.781	YES	0.529	YES	0.411
7	YES	0.332	YES	0.388	YES	0.311	YES	0.620	YES	0.420	YES	0.326
8	YES	0.321	YES	0.375	YES	0.301	YES	0.600	YES	0.406	YES	0.315
9	YES	0.493	YES	0.577	YES	0.463	YES	0.922	YES	0.625	YES	0.485
10	YES	0.485	YES	0.567	YES	0.455	YES	0.906	YES	0.614	YES	0.477
11	YES	1.319	YES	1.544	YES	1.238	NO	2.467	YES	1.672	YES	1.298
12	NO	2.899	NO	3.393	NO	2.722	NO	5.422	NO	3.674	NO	2.853
13	NO	2.421	NO	2.833	NO	2.272	NO	4.527	NO	3.068	NO	2.382
14	NO	7.822	NO	9.155	NO	7.342	NO	14.628	NO	9.913	NO	7.696
15	YES	1.330	YES	1.557	YES	1.249	NO	2.488	YES	1.686	YES	1.309
16	YES	1.158	YES	1.356	YES	1.087	NO	2.166	YES	1.468	YES	1.140
17	YES	1.820	NO	2.130	YES	1.709	NO	3.404	NO	2.307	YES	1.791
18	YES	1.062	YES	1.243	YES	0.997	YES	1.986	YES	1.346	YES	1.045
19	YES	0.734	YES	0.859	YES	0.689	YES	1.372	YES	0.930	YES	0.722
20	NO	3.250	NO	3.803	NO	3.050	NO	6.077	NO	4.118	NO	3.197
21	YES	1.391	YES	1.628	YES	1.306	NO	2.602	YES	1.763	YES	1.369
22	NO	16.697	NO	19.541	NO	15.672	NO	31.224	NO	21.159	NO	16.428
23	NO	3.294	NO	3.855	NO	3.092	NO	6.160	NO	4.174	NO	3.241
24	YES	0.743	YES	0.869	YES	0.697	YES	1.389	YES	0.941	YES	0.731
25	YES	1.030	YES	1.206	YES	0.967	YES	1.927	YES	1.306	YES	1.014
26	NO	2.001	NO	2.342	YES	1.878	NO	3.742	NO	2.536	YES	1.969
27	YES	1.658	YES	1.941	YES	1.557	NO	3.101	NO	2.101	YES	1.632
28	YES	1.093	YES	1.279	YES	1.026	NO	2.044	YES	1.385	YES	1.075
29	YES	0.966	YES	1.131	YES	0.907	YES	1.807	YES	1.225	YES	0.951
30	YES	0.593	YES	0.694	YES	0.557	YES	1.110	YES	0.752	YES	0.584
31	YES	0.479	YES	0.561	YES	0.450	YES	0.897	YES	0.608	YES	0.472
32	YES	0.521	YES	0.609	YES	0.489	YES	0.974	YES	0.660	YES	0.512
33	YES	0.990	YES	1.159	YES	0.929	YES	1.852	YES	1.255	YES	0.974
34	YES	0.448	YES	0.525	YES	0.421	YES	0.838	YES	0.568	YES	0.441
35	YES	0.564	YES	0.660	YES	0.529	YES	1.054	YES	0.714	YES	0.555
36	YES	0.414	YES	0.484	YES	0.388	YES	0.774	YES	0.524	YES	0.407
37	YES	0.321	YES	0.375	YES	0.301	YES	0.600	YES	0.406	YES	0.315
38	YES	0.403	YES	0.472	YES	0.379	YES	0.755	YES	0.511	YES	0.397
39	YES	0.323	YES	0.378	YES	0.303	YES	0.604	YES	0.409	YES	0.318
40	YES	0.372	YES	0.436	YES	0.350	YES	0.697	YES	0.472	YES	0.366
41	YES	0.301	YES	0.352	YES	0.282	YES	0.562	YES	0.381	YES	0.296
42	YES	0.407	YES	0.476	YES	0.382	YES	0.761	YES	0.516	YES	0.400
43	YES	0.488	YES	0.571	YES	0.458	YES	0.912	YES	0.618	YES	0.480
44	YES	0.346	YES	0.405	YES	0.325	YES	0.647	YES	0.438	YES	0.340
45	YES	0.397	YES	0.465	YES	0.373	YES	0.742	YES	0.503	YES	0.390

TABLE XLV (Continued)

DEPOSITION PREDICTIONS FOR MONTHLY AVERAGE
FLOW RATES OF 1969

2 Ft./Sec. Flow Criterion

	July		August		September		October		November		December	
	7 CFS=	11154.00	8 CFS=	2250.00	9 CFS=	1472.00	10 CFS=	1745.00	11 CFS=	2974.00	12 CFS=	3129.00
1	NO	11.405	NO	2.301	YES	1.505	YES	1.784	NO	3.041	NO	3.199
2	NO	2.788	YES	0.563	YES	0.368	YES	0.436	YES	0.743	YES	0.782
3	YES	1.605	YES	0.324	YES	0.212	YES	0.251	YES	0.428	YES	0.450
4	NO	18.285	NO	3.689	NO	2.413	NO	2.861	NO	4.875	NO	5.130
5	NO	15.666	NO	3.160	NO	2.067	NO	2.451	NO	4.177	NO	4.395
6	YES	0.962	YES	0.194	YES	0.127	YES	0.150	YES	0.256	YES	0.270
7	YES	0.764	YES	0.154	YES	0.101	YES	0.120	YES	0.204	YES	0.214
8	YES	0.739	YES	0.149	YES	0.097	YES	0.116	YES	0.197	YES	0.207
9	YES	1.136	YES	0.229	YES	0.150	YES	0.178	YES	0.303	YES	0.319
10	YES	1.117	YES	0.225	YES	0.147	YES	0.175	YES	0.298	YES	0.313
11	NO	3.039	YES	0.613	YES	0.401	YES	0.475	YES	0.810	YES	0.853
12	NO	6.679	YES	1.347	YES	0.881	YES	1.045	YES	1.781	YES	1.874
13	NO	5.577	YES	1.125	YES	0.736	YES	0.872	YES	1.487	YES	1.564
14	NO	18.019	NO	3.635	NO	2.378	NO	2.819	NO	4.805	NO	5.055
15	NO	3.064	YES	0.618	YES	0.404	YES	0.479	YES	0.817	YES	0.860
16	NO	2.668	YES	0.538	YES	0.352	YES	0.417	YES	0.711	YES	0.749
17	NO	4.193	YES	0.846	YES	0.553	YES	0.656	YES	1.118	YES	1.176
18	NO	2.446	YES	0.493	YES	0.323	YES	0.383	YES	0.652	YES	0.686
19	YES	1.690	YES	0.341	YES	0.223	YES	0.264	YES	0.451	YES	0.474
20	NO	7.486	YES	1.510	YES	0.988	YES	1.171	YES	1.996	NO	2.100
21	NO	3.205	YES	0.647	YES	0.423	YES	0.501	YES	0.855	YES	0.899
22	NO	38.462	NO	7.759	NO	5.076	NO	6.017	NO	10.255	NO	10.790
23	NO	7.588	YES	1.531	YES	1.001	YES	1.187	NO	2.023	NO	2.129
24	YES	1.711	YES	0.345	YES	0.226	YES	0.268	YES	0.456	YES	0.480
25	NO	2.373	YES	0.479	YES	0.313	YES	0.371	YES	0.633	YES	0.666
26	NO	4.609	YES	0.930	YES	0.608	YES	0.721	YES	1.229	YES	1.293
27	NO	3.820	YES	0.771	YES	0.504	YES	0.598	YES	1.018	YES	1.072
28	NO	2.518	YES	0.508	YES	0.332	YES	0.394	YES	0.671	YES	0.706
29	NO	2.226	YES	0.449	YES	0.294	YES	0.348	YES	0.594	YES	0.625
30	YES	1.367	YES	0.276	YES	0.180	YES	0.214	YES	0.364	YES	0.383
31	YES	1.104	YES	0.223	YES	0.146	YES	0.173	YES	0.294	YES	0.310
32	YES	1.199	YES	0.242	YES	0.158	YES	0.188	YES	0.320	YES	0.336
33	NO	2.281	YES	0.460	YES	0.301	YES	0.357	YES	0.608	YES	0.640
34	YES	1.033	YES	0.208	YES	0.136	YES	0.162	YES	0.275	YES	0.290
35	YES	1.298	YES	0.262	YES	0.171	YES	0.203	YES	0.346	YES	0.364
36	YES	0.953	YES	0.192	YES	0.126	YES	0.149	YES	0.254	YES	0.267
37	YES	0.739	YES	0.149	YES	0.097	YES	0.116	YES	0.197	YES	0.207
38	YES	0.929	YES	0.188	YES	0.123	YES	0.145	YES	0.248	YES	0.261
39	YES	0.744	YES	0.150	YES	0.098	YES	0.116	YES	0.198	YES	0.209
40	YES	0.858	YES	0.173	YES	0.113	YES	0.134	YES	0.229	YES	0.241
41	YES	0.693	YES	0.140	YES	0.091	YES	0.108	YES	0.185	YES	0.194
42	YES	0.937	YES	0.189	YES	0.124	YES	0.147	YES	0.250	YES	0.263
43	YES	1.123	YES	0.227	YES	0.148	YES	0.176	YES	0.299	YES	0.315
44	YES	0.797	YES	0.161	YES	0.105	YES	0.125	YES	0.212	YES	0.223
45	YES	0.914	YES	0.184	YES	0.121	YES	0.143	YES	0.244	YES	0.256

TABLE XLVI

DEPOSITION PREDICTIONS FOR MONTHLY AVERAGE
FLOW RATES OF 1970

1 Ft./Sec. Flow Criterion

January			February			March			April			May			June		
1 CFS=		5126.00	2 CFS=		4191.00	3 CFS=		3295.00	4 CFS=		1595.00	5 CFS=		3249.00	6 CFS=		7287.00
1	NO	5.241	1	NO	4.285	1	NO	3.369	1	NO	1.631	1	NO	3.322	1	NO	7.451
2	NO	1.281	2	NO	1.048	2	YES	0.824	2	YES	0.399	2	YES	0.812	2	NO	1.822
3	YES	0.738	3	YES	0.603	3	YES	0.474	3	YES	0.229	3	YES	0.467	3	NO	1.048
4	NO	8.403	4	NO	6.870	4	NO	5.402	4	NO	2.615	4	NO	5.326	4	NO	11.946
5	NO	7.199	5	NO	5.886	5	NO	4.628	5	NO	2.240	5	NO	4.563	5	NO	10.235
6	YES	0.442	6	YES	0.361	6	YES	0.284	6	YES	0.137	6	YES	0.280	6	YES	0.628
7	YES	0.351	7	YES	0.287	7	YES	0.226	7	YES	0.109	7	YES	0.223	7	YES	0.499
8	YES	0.339	8	YES	0.278	8	YES	0.218	8	YES	0.106	8	YES	0.215	8	YES	0.483
9	YES	0.522	9	YES	0.427	9	YES	0.336	9	YES	0.162	9	YES	0.331	9	YES	0.742
10	YES	0.513	10	YES	0.420	10	YES	0.330	10	YES	0.160	10	YES	0.325	10	YES	0.729
11	NO	1.397	11	NO	1.142	11	YES	0.898	11	YES	0.435	11	YES	0.885	11	NO	1.986
12	NO	3.069	12	NO	2.510	12	NO	1.973	12	YES	0.955	12	NO	1.946	12	NO	4.363
13	NO	2.563	13	NO	2.095	13	NO	1.647	13	YES	0.797	13	NO	1.624	13	NO	3.643
14	NO	8.281	14	NO	6.771	14	NO	5.323	14	NO	2.577	14	NO	5.249	14	NO	11.772
15	NO	1.408	15	NO	1.151	15	YES	0.905	15	YES	0.438	15	YES	0.893	15	NO	2.002
16	NO	1.226	16	NO	1.003	16	YES	0.788	16	YES	0.382	16	YES	0.777	16	NO	1.743
17	NO	1.927	17	NO	1.576	17	NO	1.239	17	YES	0.600	17	NO	1.221	17	NO	2.739
18	NO	1.124	18	YES	0.919	18	YES	0.723	18	YES	0.350	18	YES	0.712	18	NO	1.598
19	YES	0.777	19	YES	0.635	19	YES	0.499	19	YES	0.242	19	YES	0.492	19	NO	1.104
20	NO	3.440	20	NO	2.813	20	NO	2.211	20	NO	1.070	20	NO	2.181	20	NO	4.891
21	NO	1.473	21	NO	1.204	21	YES	0.947	21	YES	0.458	21	YES	0.934	21	NO	2.094
22	NO	17.676	22	NO	14.452	22	NO	11.362	22	NO	5.500	22	NO	11.203	22	NO	25.128
23	NO	3.487	23	NO	2.851	23	NO	2.241	23	NO	1.085	23	NO	2.210	23	NO	4.957
24	YES	0.786	24	YES	0.643	24	YES	0.505	24	YES	0.245	24	YES	0.498	24	NO	1.118
25	NO	1.091	25	YES	0.892	25	YES	0.701	25	YES	0.339	25	YES	0.691	25	NO	1.550
26	NO	2.118	26	NO	1.732	26	NO	1.362	26	YES	0.659	26	NO	1.343	26	NO	3.011
27	NO	1.755	27	NO	1.435	27	NO	1.128	27	YES	0.546	27	NO	1.113	27	NO	2.496
28	NO	1.157	28	YES	0.946	28	YES	0.744	28	YES	0.360	28	YES	0.733	28	NO	1.645
29	NO	1.023	29	YES	0.837	29	YES	0.658	29	YES	0.318	29	YES	0.649	29	NO	1.454
30	YES	0.628	30	YES	0.514	30	YES	0.404	30	YES	0.195	30	YES	0.398	30	YES	0.893
31	YES	0.508	31	YES	0.415	31	YES	0.326	31	YES	0.158	31	YES	0.322	31	YES	0.721
32	YES	0.551	32	YES	0.451	32	YES	0.354	32	YES	0.172	32	YES	0.349	32	YES	0.784
33	NO	1.048	33	YES	0.857	33	YES	0.674	33	YES	0.326	33	YES	0.664	33	NO	1.490
34	YES	0.475	34	YES	0.388	34	YES	0.305	34	YES	0.148	34	YES	0.301	34	YES	0.675
35	YES	0.597	35	YES	0.488	35	YES	0.384	35	YES	0.186	35	YES	0.378	35	YES	0.848
36	YES	0.438	36	YES	0.358	36	YES	0.282	36	YES	0.136	36	YES	0.278	36	YES	0.623
37	YES	0.339	37	YES	0.278	37	YES	0.218	37	YES	0.106	37	YES	0.215	37	YES	0.483
38	YES	0.427	38	YES	0.349	38	YES	0.275	38	YES	0.133	38	YES	0.271	38	YES	0.607
39	YES	0.342	39	YES	0.279	39	YES	0.220	39	YES	0.106	39	YES	0.217	39	YES	0.486
40	YES	0.394	40	YES	0.322	40	YES	0.253	40	YES	0.123	40	YES	0.250	40	YES	0.561
41	YES	0.318	41	YES	0.260	41	YES	0.205	41	YES	0.099	41	YES	0.202	41	YES	0.453
42	YES	0.431	42	YES	0.352	42	YES	0.277	42	YES	0.134	42	YES	0.273	42	YES	0.612
43	YES	0.516	43	YES	0.422	43	YES	0.332	43	YES	0.161	43	YES	0.327	43	YES	0.734
44	YES	0.366	44	YES	0.299	44	YES	0.235	44	YES	0.114	44	YES	0.232	44	YES	0.520
45	YES	0.420	45	YES	0.344	45	YES	0.270	45	YES	0.131	45	YES	0.266	45	YES	0.597

TABLE XLVI (Continued)

DEPOSITION PREDICTIONS FOR MONTHLY AVERAGE
FLOW RATES OF 1970

1 Ft./Sec. Flow Criterion

July			August			September		
7	CFS=	1631.00	8	CFS=	1350.00	9	CFS=	1498.00
1	NO	1.668	1	NO	1.380	1	NO	1.532
2	YES	0.408	2	YES	0.337	2	YES	0.374
3	YES	0.235	3	YES	0.194	3	YES	0.216
4	NO	2.674	4	NO	2.213	4	NO	2.456
5	NO	2.291	5	NO	1.896	5	NO	2.104
6	YES	0.141	6	YES	0.116	6	YES	0.129
7	YES	0.112	7	YES	0.092	7	YES	0.103
8	YES	0.108	8	YES	0.089	8	YES	0.099
9	YES	0.166	9	YES	0.137	9	YES	0.153
10	YES	0.163	10	YES	0.135	10	YES	0.150
11	YES	0.444	11	YES	0.368	11	YES	0.408
12	YES	0.977	12	YES	0.808	12	YES	0.897
13	YES	0.815	13	YES	0.675	13	YES	0.749
14	NO	2.635	14	NO	2.181	14	NO	2.420
15	YES	0.448	15	YES	0.371	15	YES	0.412
16	YES	0.390	16	YES	0.323	16	YES	0.358
17	YES	0.613	17	YES	0.508	17	YES	0.563
18	YES	0.358	18	YES	0.296	18	YES	0.329
19	YES	0.247	19	YES	0.205	19	YES	0.227
20	NO	1.095	20	YES	0.906	20	NO	1.005
21	YES	0.469	21	YES	0.388	21	YES	0.430
22	NO	5.624	22	NO	4.655	22	NO	5.166
23	NO	1.110	23	YES	0.918	23	NO	1.019
24	YES	0.250	24	YES	0.207	24	YES	0.230
25	YES	0.347	25	YES	0.287	25	YES	0.319
26	YES	0.674	26	YES	0.558	26	YES	0.619
27	YES	0.559	27	YES	0.462	27	YES	0.513
28	YES	0.368	28	YES	0.305	28	YES	0.338
29	YES	0.326	29	YES	0.269	29	YES	0.299
30	YES	0.200	30	YES	0.165	30	YES	0.184
31	YES	0.161	31	YES	0.134	31	YES	0.148
32	YES	0.175	32	YES	0.145	32	YES	0.161
33	YES	0.334	33	YES	0.276	33	YES	0.306
34	YES	0.151	34	YES	0.125	34	YES	0.139
35	YES	0.190	35	YES	0.157	35	YES	0.174
36	YES	0.139	36	YES	0.115	36	YES	0.128
37	YES	0.108	37	YES	0.089	37	YES	0.099
38	YES	0.136	38	YES	0.112	38	YES	0.125
39	YES	0.109	39	YES	0.090	39	YES	0.100
40	YES	0.125	40	YES	0.104	40	YES	0.115
41	YES	0.101	41	YES	0.084	41	YES	0.093
42	YES	0.137	42	YES	0.113	42	YES	0.126
43	YES	0.164	43	YES	0.136	43	YES	0.151
44	YES	0.116	44	YES	0.096	44	YES	0.107
45	YES	0.134	45	YES	0.111	45	YES	0.123

October			November			December		
10	CFS=	1701.00	11	CFS=	4998.00	12	CFS=	3116.00
1	NO	1.739	1	NO	5.110	1	NO	3.186
2	YES	0.425	2	NO	1.249	2	YES	0.779
3	YES	0.245	3	YES	0.719	3	YES	0.448
4	NO	2.789	4	NO	8.193	4	NO	5.108
5	NO	2.389	5	NO	7.020	5	NO	4.376
6	YES	0.147	6	YES	0.431	6	YES	0.269
7	YES	0.117	7	YES	0.342	7	YES	0.213
8	YES	0.113	8	YES	0.331	8	YES	0.206
9	YES	0.173	9	YES	0.509	9	YES	0.317
10	YES	0.170	10	YES	0.500	10	YES	0.312
11	YES	0.463	11	NO	1.362	11	YES	0.849
12	NO	1.019	12	NO	2.993	12	NO	1.866
13	YES	0.850	13	NO	2.499	13	NO	1.558
14	NO	2.748	14	NO	8.074	14	NO	5.034
15	YES	0.467	15	NO	1.373	15	YES	0.856
16	YES	0.407	16	NO	1.196	16	YES	0.745
17	YES	0.639	17	NO	1.879	17	NO	1.171
18	YES	0.373	18	NO	1.096	18	YES	0.683
19	YES	0.258	19	YES	0.757	19	YES	0.472
20	NO	1.142	20	NO	3.354	20	NO	2.091
21	YES	0.489	21	NO	1.436	21	YES	0.895
22	NO	5.866	22	NO	17.234	22	NO	10.745
23	NO	1.157	23	NO	3.400	23	NO	2.120
24	YES	0.261	24	YES	0.767	24	YES	0.478
25	YES	0.362	25	NO	1.063	25	YES	0.663
26	YES	0.703	26	NO	2.065	26	NO	1.288
27	YES	0.583	27	NO	1.712	27	NO	1.067
28	YES	0.384	28	NO	1.128	28	YES	0.703
29	YES	0.340	29	YES	0.998	29	YES	0.622
30	YES	0.208	30	YES	0.612	30	YES	0.382
31	YES	0.168	31	YES	0.495	31	YES	0.309
32	YES	0.183	32	YES	0.537	32	YES	0.335
33	YES	0.348	33	NO	1.022	33	YES	0.637
34	YES	0.157	34	YES	0.463	34	YES	0.289
35	YES	0.198	35	YES	0.582	35	YES	0.363
36	YES	0.145	36	YES	0.427	36	YES	0.266
37	YES	0.113	37	YES	0.331	37	YES	0.206
38	YES	0.142	38	YES	0.416	38	YES	0.260
39	YES	0.113	39	YES	0.333	39	YES	0.208
40	YES	0.131	40	YES	0.384	40	YES	0.240
41	YES	0.106	41	YES	0.310	41	YES	0.194
42	YES	0.143	42	YES	0.420	42	YES	0.262
43	YES	0.171	43	YES	0.503	43	YES	0.314
44	YES	0.121	44	YES	0.357	44	YES	0.223
45	YES	0.139	45	YES	0.410	45	YES	0.255

TABLE XLVII

DEPOSITION PREDICTIONS FOR MONTHLY AVERAGE FLOW RATES OF 1970

2 Ft./Sec. Flow Criterion

	January		February		March		April		May		June	
	1 CFS=	5126.00	2 CFS=	4191.00	3 CFS=	3295.00	4 CFS=	1595.00	5 CFS=	3249.00	6 CFS=	7287.00
1	NO	5.241	NO	4.285	NO	3.369	YES	1.631	NO	3.322	NO	7.451
2	YES	1.281	YES	1.048	YES	0.824	YES	0.399	YES	0.812	YES	1.822
3	YES	0.738	YES	0.603	YES	0.474	YES	0.229	YES	0.467	YES	1.048
4	NO	8.403	NO	6.870	NO	5.402	NO	2.615	NO	5.326	NO	11.946
5	NO	7.199	NO	5.886	NO	4.628	NO	2.240	NO	4.563	NO	10.235
6	YES	0.442	YES	0.361	YES	0.284	YES	0.137	YES	0.280	YES	0.628
7	YES	0.351	YES	0.287	YES	0.226	YES	0.109	YES	0.223	YES	0.499
8	YES	0.339	YES	0.278	YES	0.218	YES	0.106	YES	0.215	YES	0.483
9	YES	0.522	YES	0.427	YES	0.336	YES	0.162	YES	0.331	YES	0.742
10	YES	0.513	YES	0.420	YES	0.330	YES	0.160	YES	0.325	YES	0.729
11	YES	1.397	YES	1.142	YES	0.898	YES	0.435	YES	0.885	YES	1.986
12	NO	3.069	NO	2.510	YES	1.973	YES	0.955	YES	1.946	NO	4.363
13	NO	2.563	NO	2.095	YES	1.647	YES	0.797	YES	1.624	NO	3.643
14	NO	8.281	NO	6.771	NO	5.323	NO	2.577	NO	5.249	NO	11.772
15	YES	1.408	YES	1.151	YES	0.905	YES	0.438	YES	0.893	NO	2.002
16	YES	1.226	YES	1.003	YES	0.788	YES	0.382	YES	0.777	YES	1.743
17	YES	1.927	YES	1.576	YES	1.239	YES	0.600	YES	1.221	NO	2.739
18	YES	1.124	YES	0.919	YES	0.723	YES	0.350	YES	0.712	YES	1.598
19	YES	0.777	YES	0.635	YES	0.499	YES	0.242	YES	0.492	YES	1.104
20	NO	3.440	NO	2.813	NO	2.211	YES	1.070	NO	2.181	NO	4.891
21	YES	1.473	YES	1.204	YES	0.947	YES	0.458	YES	0.934	NO	2.094
22	NO	17.676	NO	14.452	NO	11.362	NO	5.500	NO	11.203	NO	25.128
23	NO	3.487	NO	2.851	NO	2.241	YES	1.085	NO	2.210	NO	4.957
24	YES	0.786	YES	0.643	YES	0.505	YES	0.245	YES	0.498	YES	1.118
25	YES	1.091	YES	0.892	YES	0.701	YES	0.339	YES	0.691	YES	1.550
26	NO	2.118	YES	1.732	YES	1.362	YES	0.659	YES	1.343	NO	3.011
27	YES	1.755	YES	1.435	YES	1.128	YES	0.546	YES	1.113	NO	2.496
28	YES	1.157	YES	0.946	YES	0.744	YES	0.360	YES	0.733	YES	1.645
29	YES	1.023	YES	0.837	YES	0.658	YES	0.318	YES	0.649	YES	1.454
30	YES	0.628	YES	0.514	YES	0.404	YES	0.195	YES	0.398	YES	0.893
31	YES	0.508	YES	0.415	YES	0.326	YES	0.158	YES	0.322	YES	0.721
32	YES	0.551	YES	0.451	YES	0.354	YES	0.172	YES	0.349	YES	0.784
33	YES	1.048	YES	0.857	YES	0.674	YES	0.326	YES	0.664	YES	1.490
34	YES	0.475	YES	0.388	YES	0.305	YES	0.148	YES	0.301	YES	0.675
35	YES	0.597	YES	0.488	YES	0.384	YES	0.186	YES	0.378	YES	0.848
36	YES	0.438	YES	0.358	YES	0.282	YES	0.136	YES	0.278	YES	0.623
37	YES	0.339	YES	0.278	YES	0.218	YES	0.106	YES	0.215	YES	0.483
38	YES	0.427	YES	0.349	YES	0.275	YES	0.133	YES	0.271	YES	0.607
39	YES	0.342	YES	0.279	YES	0.220	YES	0.106	YES	0.217	YES	0.486
40	YES	0.394	YES	0.322	YES	0.253	YES	0.123	YES	0.250	YES	0.561
41	YES	0.318	YES	0.260	YES	0.205	YES	0.099	YES	0.202	YES	0.453
42	YES	0.431	YES	0.352	YES	0.277	YES	0.134	YES	0.273	YES	0.612
43	YES	0.516	YES	0.422	YES	0.332	YES	0.161	YES	0.327	YES	0.734
44	YES	0.366	YES	0.299	YES	0.235	YES	0.114	YES	0.232	YES	0.520
45	YES	0.420	YES	0.344	YES	0.270	YES	0.131	YES	0.266	YES	0.597

TABLE XLVII (Continued)

DEPOSITION PREDICTIONS FOR MONTHLY AVERAGE
FLOW RATES OF 1970

2 Ft./Sec. Flow Criterion

July			August			September			October			November			December		
7	CFS=	1631.00	8	CFS=	1350.00	9	CFS=	1498.00	10	CFS=	1701.00	11	CFS=	4998.00	12	CFS=	3116.00
1	YES	1.668	1	YES	1.380	1	YES	1.532	1	YES	1.739	1	NO	5.110	1	NO	3.186
2	YES	0.408	2	YES	0.337	2	YES	0.374	2	YES	0.425	2	YES	1.249	2	YES	0.779
3	YES	0.235	3	YES	0.194	3	YES	0.216	3	YES	0.245	3	YES	0.719	3	YES	0.448
4	NO	2.674	4	NO	2.213	4	NO	2.456	4	NO	2.789	4	NO	8.193	4	NO	5.108
5	NO	2.291	5	YES	1.896	5	NO	2.104	5	NO	2.389	5	NO	7.020	5	NO	4.376
6	YES	0.141	6	YES	0.116	6	YES	0.129	6	YES	0.147	6	YES	0.431	6	YES	0.269
7	YES	0.112	7	YES	0.092	7	YES	0.103	7	YES	0.117	7	YES	0.342	7	YES	0.213
8	YES	0.108	8	YES	0.089	8	YES	0.099	8	YES	0.113	8	YES	0.331	8	YES	0.206
9	YES	0.166	9	YES	0.137	9	YES	0.153	9	YES	0.173	9	YES	0.509	9	YES	0.317
10	YES	0.163	10	YES	0.135	10	YES	0.150	10	YES	0.170	10	YES	0.500	10	YES	0.312
11	YES	0.444	11	YES	0.368	11	YES	0.408	11	YES	0.463	11	YES	1.362	11	YES	0.849
12	YES	0.977	12	YES	0.808	12	YES	0.897	12	YES	1.019	12	NO	2.993	12	YES	1.866
13	YES	0.815	13	YES	0.675	13	YES	0.749	13	YES	0.850	13	NO	2.499	13	YES	1.558
14	NO	2.635	14	NO	2.181	14	NO	2.420	14	NO	2.748	14	NO	8.074	14	NO	5.034
15	YES	0.448	15	YES	0.371	15	YES	0.412	15	YES	0.467	15	YES	1.373	15	YES	0.856
16	YES	0.390	16	YES	0.323	16	YES	0.358	16	YES	0.407	16	YES	1.196	16	YES	0.745
17	YES	0.613	17	YES	0.508	17	YES	0.563	17	YES	0.639	17	YES	1.879	17	YES	1.171
18	YES	0.358	18	YES	0.296	18	YES	0.329	18	YES	0.373	18	YES	1.096	18	YES	0.683
19	YES	0.247	19	YES	0.205	19	YES	0.227	19	YES	0.258	19	YES	0.757	19	YES	0.472
20	YES	1.095	20	YES	0.906	20	YES	1.005	20	YES	1.142	20	NO	3.354	20	NO	2.091
21	YES	0.469	21	YES	0.388	21	YES	0.430	21	YES	0.489	21	YES	1.436	21	YES	0.895
22	NO	5.624	22	NO	4.655	22	NO	5.166	22	NO	5.866	22	NO	17.234	22	NO	10.745
23	YES	1.110	23	YES	0.918	23	YES	1.019	23	YES	1.157	23	NO	3.400	23	NO	2.120
24	YES	0.250	24	YES	0.207	24	YES	0.230	24	YES	0.261	24	YES	0.767	24	YES	0.478
25	YES	0.347	25	YES	0.287	25	YES	0.319	25	YES	0.362	25	YES	1.063	25	YES	0.663
26	YES	0.674	26	YES	0.558	26	YES	0.619	26	YES	0.703	26	NO	2.065	26	YES	1.288
27	YES	0.559	27	YES	0.462	27	YES	0.513	27	YES	0.583	27	YES	1.712	27	YES	1.067
28	YES	0.368	28	YES	0.305	28	YES	0.338	28	YES	0.384	28	YES	1.128	28	YES	0.703
29	YES	0.326	29	YES	0.269	29	YES	0.299	29	YES	0.340	29	YES	0.998	29	YES	0.622
30	YES	0.200	30	YES	0.165	30	YES	0.184	30	YES	0.208	30	YES	0.612	30	YES	0.382
31	YES	0.161	31	YES	0.134	31	YES	0.148	31	YES	0.168	31	YES	0.495	31	YES	0.309
32	YES	0.175	32	YES	0.145	32	YES	0.161	32	YES	0.183	32	YES	0.537	32	YES	0.335
33	YES	0.334	33	YES	0.276	33	YES	0.306	33	YES	0.348	33	YES	1.022	33	YES	0.637
34	YES	0.151	34	YES	0.125	34	YES	0.139	34	YES	0.157	34	YES	0.463	34	YES	0.289
35	YES	0.190	35	YES	0.157	35	YES	0.174	35	YES	0.198	35	YES	0.582	35	YES	0.363
36	YES	0.139	36	YES	0.115	36	YES	0.128	36	YES	0.145	36	YES	0.427	36	YES	0.266
37	YES	0.108	37	YES	0.089	37	YES	0.099	37	YES	0.113	37	YES	0.331	37	YES	0.206
38	YES	0.136	38	YES	0.112	38	YES	0.125	38	YES	0.142	38	YES	0.416	38	YES	0.260
39	YES	0.109	39	YES	0.090	39	YES	0.100	39	YES	0.113	39	YES	0.333	39	YES	0.208
40	YES	0.125	40	YES	0.104	40	YES	0.115	40	YES	0.131	40	YES	0.384	40	YES	0.240
41	YES	0.101	41	YES	0.084	41	YES	0.093	41	YES	0.106	41	YES	0.310	41	YES	0.194
42	YES	0.137	42	YES	0.113	42	YES	0.126	42	YES	0.143	42	YES	0.420	42	YES	0.262
43	YES	0.164	43	YES	0.136	43	YES	0.151	43	YES	0.171	43	YES	0.503	43	YES	0.314
44	YES	0.116	44	YES	0.096	44	YES	0.107	44	YES	0.121	44	YES	0.357	44	YES	0.223
45	YES	0.134	45	YES	0.111	45	YES	0.123	45	YES	0.139	45	YES	0.410	45	YES	0.255

TABLE XLVIII

DEPOSTION PREDICTIONS FOR MONTHLY AVERAGE FLOW RATES OF 1971

1 Ft./Sec. Flow Criterion

January			February			March		
1	CFS=	3380.00	2	CFS=	4333.00	3	CFS=	6955.00
1	NO	3.456	1	NO	4.430	1	NO	7.111
2	YES	0.845	2	NO	1.083	2	NO	1.739
3	YES	0.486	3	YES	0.623	3	NO	1.001
4	NO	5.541	4	NO	7.103	4	NO	11.402
5	NO	4.747	5	NO	6.086	5	NO	9.768
6	YES	0.291	6	YES	0.374	6	YES	0.600
7	YES	0.232	7	YES	0.297	7	YES	0.476
8	YES	0.224	8	YES	0.287	8	YES	0.461
9	YES	0.344	9	YES	0.441	9	YES	0.708
10	YES	0.338	10	YES	0.434	10	YES	0.696
11	YES	0.921	11	NO	1.181	11	NO	1.895
12	NO	2.024	12	NO	2.595	12	NO	4.165
13	NO	1.690	13	NO	2.166	13	NO	3.477
14	NO	5.460	14	NO	7.000	14	NO	11.236
15	YES	0.929	15	NO	1.190	15	NO	1.911
16	YES	0.809	16	NO	1.037	16	NO	1.664
17	NO	1.271	17	NO	1.629	17	NO	2.615
18	YES	0.741	18	YES	0.950	18	NO	1.525
19	YES	0.512	19	YES	0.657	19	NO	1.054
20	NO	2.268	20	NO	2.908	20	NO	4.668
21	YES	0.971	21	NO	1.245	21	NO	1.999
22	NO	11.655	22	NO	14.941	22	NO	23.983
23	NO	2.299	23	NO	2.948	23	NO	4.731
24	YES	0.518	24	YES	0.665	24	NO	1.067
25	YES	0.719	25	YES	0.922	25	NO	1.480
26	NO	1.397	26	NO	1.790	26	NO	2.874
27	NO	1.158	27	NO	1.484	27	NO	2.382
28	YES	0.763	28	YES	0.978	28	NO	1.570
29	YES	0.675	29	YES	0.865	29	NO	1.388
30	YES	0.414	30	YES	0.531	30	YES	0.852
31	YES	0.335	31	YES	0.429	31	YES	0.689
32	YES	0.363	32	YES	0.466	32	YES	0.748
33	YES	0.691	33	YES	0.886	33	NO	1.422
34	YES	0.313	34	YES	0.401	34	YES	0.644
35	YES	0.393	35	YES	0.504	35	YES	0.810
36	YES	0.289	36	YES	0.370	36	YES	0.594
37	YES	0.224	37	YES	0.287	37	YES	0.461
38	YES	0.282	38	YES	0.361	38	YES	0.580
39	YES	0.225	39	YES	0.289	39	YES	0.464
40	YES	0.260	40	YES	0.333	40	YES	0.535
41	YES	0.210	41	YES	0.269	41	YES	0.432
42	YES	0.284	42	YES	0.364	42	YES	0.584
43	YES	0.340	43	YES	0.436	43	YES	0.700
44	YES	0.241	44	YES	0.309	44	YES	0.497
45	YES	0.277	45	YES	0.355	45	YES	0.570

April			May			June		
4	CFS=	8092.00	5	CFS=	4798.00	6	CFS=	4368.00
1	NO	8.274	1	NO	4.906	1	NO	4.466
2	NO	2.023	2	NO	1.199	2	NO	1.092
3	NO	1.164	3	YES	0.690	3	YES	0.628
4	NO	13.266	4	NO	7.866	4	NO	7.161
5	NO	11.365	5	NO	6.739	5	NO	6.135
6	YES	0.698	6	YES	0.414	6	YES	0.377
7	YES	0.554	7	YES	0.329	7	YES	0.299
8	YES	0.536	8	YES	0.318	8	YES	0.289
9	YES	0.824	9	YES	0.489	9	YES	0.445
10	YES	0.810	10	YES	0.480	10	YES	0.437
11	NO	2.205	11	NO	1.307	11	NO	1.190
12	NO	4.846	12	NO	2.873	12	NO	2.616
13	NO	4.046	13	NO	2.399	13	NO	2.184
14	NO	13.073	14	NO	7.751	14	NO	7.057
15	NO	2.223	15	NO	1.318	15	NO	1.200
16	NO	1.936	16	NO	1.148	16	NO	1.045
17	NO	3.042	17	NO	1.804	17	NO	1.642
18	NO	1.775	18	NO	1.052	18	YES	0.958
19	NO	1.226	19	YES	0.727	19	YES	0.662
20	NO	5.431	20	NO	3.220	20	NO	2.932
21	NO	2.325	21	NO	1.379	21	NO	1.255
22	NO	27.903	22	NO	16.545	22	NO	15.062
23	NO	5.505	23	NO	3.264	23	NO	2.971
24	NO	1.241	24	YES	0.736	24	YES	0.670
25	NO	1.722	25	NO	1.021	25	YES	0.929
26	NO	3.344	26	NO	1.983	26	NO	1.805
27	NO	2.771	27	NO	1.643	27	NO	1.496
28	NO	1.827	28	NO	1.083	28	YES	0.986
29	NO	1.615	29	YES	0.958	29	YES	0.872
30	YES	0.992	30	YES	0.588	30	YES	0.535
31	YES	0.801	31	YES	0.475	31	YES	0.432
32	YES	0.870	32	YES	0.516	32	YES	0.470
33	NO	1.655	33	YES	0.981	33	YES	0.893
34	YES	0.749	34	YES	0.444	34	YES	0.404
35	YES	0.942	35	YES	0.559	35	YES	0.508
36	YES	0.692	36	YES	0.410	36	YES	0.373
37	YES	0.536	37	YES	0.318	37	YES	0.289
38	YES	0.674	38	YES	0.400	38	YES	0.364
39	YES	0.539	39	YES	0.320	39	YES	0.291
40	YES	0.622	40	YES	0.369	40	YES	0.336
41	YES	0.503	41	YES	0.298	41	YES	0.271
42	YES	0.680	42	YES	0.403	42	YES	0.367
43	YES	0.815	43	YES	0.483	43	YES	0.440
44	YES	0.578	44	YES	0.343	44	YES	0.312
45	YES	0.663	45	YES	0.393	45	YES	0.358

TABLE XLVIII (Continued)

DEPOSITION PREDICTIONS FOR MONTHLY AVERAGE
FLOW RATES OF 1971

1 Ft./Sec. Flow Criterion

July			August			September			October			November		
7	CFS=	2205.00	8	CFS=	1950.00	9	CFS=	1663.00	10	CFS=	1814.00	11	CFS=	3714.00
1	NO	2.255	1	NO	1.994	1	NC	1.700	1	NO	1.855	1	NO	3.798
2	YES	0.551	2	YES	0.487	2	YES	0.416	2	YES	0.453	2	YES	0.928
3	YES	0.317	3	YES	0.281	3	YES	0.239	3	YES	0.261	3	YES	0.534
4	NO	3.615	4	NO	3.197	4	NO	2.726	4	NO	2.974	4	NO	6.089
5	NO	3.097	5	NO	2.739	5	NO	2.336	5	NO	2.548	5	NO	5.216
6	YES	0.190	6	YES	0.168	6	YES	0.143	6	YES	0.156	6	YES	0.320
7	YES	0.151	7	YES	0.134	7	YES	0.114	7	YES	0.124	7	YES	0.254
8	YES	0.146	8	YES	0.129	8	YES	0.110	8	YES	0.120	8	YES	0.246
9	YES	0.225	9	YES	0.199	9	YES	0.169	9	YES	0.185	9	YES	0.378
10	YES	0.221	10	YES	0.195	10	YES	0.166	10	YES	0.182	10	YES	0.372
11	YES	0.601	11	YES	0.531	11	YES	0.453	11	YES	0.494	11	NO	1.012
12	NO	1.320	12	NO	1.168	12	YES	0.996	12	NO	1.086	12	NO	2.224
13	NO	1.102	13	YES	0.975	13	YES	0.831	13	YES	0.907	13	NO	1.857
14	NO	3.562	14	NO	3.150	14	NO	2.687	14	NO	2.931	14	NO	6.000
15	YES	0.606	15	YES	0.536	15	YES	0.457	15	YES	0.498	15	NO	1.020
16	YES	0.528	16	YES	0.467	16	YES	0.398	16	YES	0.434	16	YES	0.889
17	YES	0.829	17	YES	0.733	17	YES	0.625	17	YES	0.682	17	NO	1.396
18	YES	0.484	18	YES	0.428	18	YES	0.365	18	YES	0.398	18	YES	0.814
19	YES	0.334	19	YES	0.295	19	YES	0.252	19	YES	0.275	19	YES	0.563
20	NO	1.480	20	NO	1.309	20	NO	1.116	20	NO	1.217	20	NO	2.493
21	YES	0.634	21	YES	0.560	21	YES	0.478	21	YES	0.521	21	NO	1.067
22	NO	7.603	22	NO	6.724	22	NO	5.734	22	NO	6.255	22	NO	12.807
23	NO	1.500	23	NO	1.327	23	NO	1.131	23	NO	1.234	23	NO	2.527
24	YES	0.338	24	YES	0.299	24	YES	0.255	24	YES	0.278	24	YES	0.570
25	YES	0.469	25	YES	0.415	25	YES	0.354	25	YES	0.386	25	YES	0.790
26	YES	0.911	26	YES	0.806	26	YES	0.687	26	YES	0.750	26	NO	1.535
27	YES	0.755	27	YES	0.668	27	YES	0.570	27	YES	0.621	27	NO	1.272
28	YES	0.498	28	YES	0.440	28	YES	0.375	28	YES	0.409	28	YES	0.838
29	YES	0.440	29	YES	0.389	29	YES	0.332	29	YES	0.362	29	YES	0.741
30	YES	0.270	30	YES	0.239	30	YES	0.204	30	YES	0.222	30	YES	0.455
31	YES	0.218	31	YES	0.193	31	YES	0.165	31	YES	0.180	31	YES	0.368
32	YES	0.237	32	YES	0.210	32	YES	0.179	32	YES	0.195	32	YES	0.399
33	YES	0.451	33	YES	0.399	33	YES	0.340	33	YES	0.371	33	YES	0.760
34	YES	0.204	34	YES	0.181	34	YES	0.154	34	YES	0.168	34	YES	0.344
35	YES	0.257	35	YES	0.227	35	YES	0.194	35	YES	0.211	35	YES	0.432
36	YES	0.188	36	YES	0.167	36	YES	0.142	36	YES	0.155	36	YES	0.317
37	YES	0.146	37	YES	0.129	37	YES	0.110	37	YES	0.120	37	YES	0.246
38	YES	0.184	38	YES	0.162	38	YES	0.139	38	YES	0.151	38	YES	0.309
39	YES	0.147	39	YES	0.130	39	YES	0.111	39	YES	0.121	39	YES	0.248
40	YES	0.170	40	YES	0.150	40	YES	0.128	40	YES	0.140	40	YES	0.286
41	YES	0.137	41	YES	0.121	41	YES	0.103	41	YES	0.113	41	YES	0.231
42	YES	0.185	42	YES	0.164	42	YES	0.140	42	YES	0.152	42	YES	0.312
43	YES	0.222	43	YES	0.196	43	YES	0.167	43	YES	0.183	43	YES	0.374
44	YES	0.157	44	YES	0.139	44	YES	0.119	44	YES	0.130	44	YES	0.265
45	YES	0.181	45	YES	0.160	45	YES	0.136	45	YES	0.149	45	YES	0.304

TABLE XLIX

DEPOSITION PREDICTIONS FOR MONTHLY AVERAGE FLOW RATES OF 1971

2 Ft./Sec. Flow Criterion

	January		February		March		April		May		June	
	1 CFS=	3380.00	2 CFS=	4333.00	3 CFS=	6955.00	4 CFS=	8092.00	5 CFS=	4798.00	6 CFS=	4368.00
1	NO	3.456	NO	4.430	NO	7.111	NO	8.274	NO	4.906	NO	4.466
2	YES	0.845	YES	1.083	YES	1.739	NO	2.023	YES	1.199	YES	1.092
3	YES	0.486	YES	0.623	YES	1.001	YES	1.164	YES	0.690	YES	0.628
4	NO	5.541	NO	7.103	NO	11.402	NO	13.266	NO	7.866	NO	7.161
5	NO	4.747	NO	6.086	NO	9.768	NO	11.365	NO	6.739	NO	6.135
6	YES	0.291	YES	0.374	YES	0.600	YES	0.698	YES	0.414	YES	0.377
7	YES	0.232	YES	0.297	YES	0.476	YES	0.554	YES	0.329	YES	0.299
8	YES	0.224	YES	0.287	YES	0.461	YES	0.536	YES	0.318	YES	0.289
9	YES	0.344	YES	0.441	YES	0.708	YES	0.824	YES	0.489	YES	0.445
10	YES	0.338	YES	0.434	YES	0.696	YES	0.810	YES	0.480	YES	0.437
11	YES	0.921	YES	1.181	YES	1.895	NO	2.205	YES	1.307	YES	1.190
12	NO	2.024	NO	2.595	NO	4.165	NO	4.846	NO	2.873	NO	2.616
13	YES	1.690	NO	2.166	NO	3.477	NO	4.046	NO	2.399	NO	2.184
14	NO	5.460	NO	7.000	NO	11.236	NO	13.073	NO	7.751	NO	7.057
15	YES	0.929	YES	1.190	YES	1.911	NO	2.223	YES	1.318	YES	1.200
16	YES	0.809	YES	1.037	YES	1.664	YES	1.936	YES	1.148	YES	1.045
17	YES	1.271	YES	1.629	NO	2.615	NO	3.042	YES	1.804	YES	1.642
18	YES	0.741	YES	0.950	YES	1.525	YES	1.775	YES	1.052	YES	0.958
19	YES	0.512	YES	0.657	YES	1.054	YES	1.226	YES	0.727	YES	0.662
20	NO	2.268	NO	2.908	NO	4.668	NO	5.431	NO	3.220	NO	2.932
21	YES	0.971	YES	1.245	YES	1.999	NO	2.325	YES	1.379	YES	1.255
22	NO	11.655	NO	14.941	NO	23.983	NO	27.903	NO	16.545	NO	15.062
23	NO	2.299	NO	2.948	NO	4.731	NO	5.505	NO	3.264	NO	2.971
24	YES	0.518	YES	0.665	YES	1.067	YES	1.241	YES	0.736	YES	0.670
25	YES	0.719	YES	0.922	YES	1.480	YES	1.722	YES	1.021	YES	0.929
26	YES	1.397	YES	1.790	NO	2.874	NO	3.344	YES	1.983	YES	1.805
27	YES	1.158	YES	1.484	NO	2.382	NO	2.771	YES	1.643	YES	1.496
28	YES	0.763	YES	0.978	YES	1.570	YES	1.827	YES	1.083	YES	0.986
29	YES	0.675	YES	0.865	YES	1.388	YES	1.615	YES	0.958	YES	0.872
30	YES	0.414	YES	0.531	YES	0.852	YES	0.992	YES	0.588	YES	0.535
31	YES	0.335	YES	0.429	YES	0.689	YES	0.801	YES	0.475	YES	0.432
32	YES	0.363	YES	0.466	YES	0.748	YES	0.870	YES	0.516	YES	0.470
33	YES	0.691	YES	0.886	YES	1.422	YES	1.655	YES	0.981	YES	0.893
34	YES	0.313	YES	0.401	YES	0.644	YES	0.749	YES	0.444	YES	0.404
35	YES	0.393	YES	0.504	YES	0.810	YES	0.942	YES	0.559	YES	0.508
36	YES	0.289	YES	0.370	YES	0.594	YES	0.692	YES	0.410	YES	0.373
37	YES	0.224	YES	0.287	YES	0.461	YES	0.536	YES	0.318	YES	0.289
38	YES	0.282	YES	0.361	YES	0.580	YES	0.674	YES	0.400	YES	0.364
39	YES	0.225	YES	0.289	YES	0.464	YES	0.539	YES	0.320	YES	0.291
40	YES	0.260	YES	0.333	YES	0.535	YES	0.622	YES	0.369	YES	0.336
41	YES	0.210	YES	0.269	YES	0.432	YES	0.503	YES	0.298	YES	0.271
42	YES	0.284	YES	0.364	YES	0.584	YES	0.680	YES	0.403	YES	0.367
43	YES	0.340	YES	0.436	YES	0.700	YES	0.815	YES	0.483	YES	0.440
44	YES	0.241	YES	0.309	YES	0.497	YES	0.578	YES	0.343	YES	0.312
45	YES	0.277	YES	0.355	YES	0.570	YES	0.663	YES	0.393	YES	0.358

TABLE XLIX (Continued)

DEPOSITION PREDICTIONS FOR MONTHLY AVERAGE
FLOW RATES OF 1971

2 Ft./Sec. Flow Criterion

	July		August		September		October		November	
	7 CFS=	2205.00	8 CFS=	1950.00	9 CFS=	1663.00	10 CFS=	1814.00	11 CFS=	3714.00
1	NO	2.255	YES	1.994	YES	1.700	YES	1.855	NO	3.798
2	YES	0.551	YES	0.487	YES	0.416	YES	0.453	YES	0.928
3	YES	0.317	YES	0.281	YES	0.239	YES	0.261	YES	0.534
4	NO	3.615	NO	3.197	NO	2.726	NO	2.974	NO	6.089
5	NO	3.097	NO	2.739	NO	2.336	NO	2.548	NO	5.216
6	YES	0.190	YES	0.168	YES	0.143	YES	0.156	YES	0.320
7	YES	0.151	YES	0.134	YES	0.114	YES	0.124	YES	0.254
8	YES	0.146	YES	0.129	YES	0.110	YES	0.120	YES	0.246
9	YES	0.225	YES	0.199	YES	0.169	YES	0.185	YES	0.378
10	YES	0.221	YES	0.195	YES	0.166	YES	0.182	YES	0.372
11	YES	0.601	YES	0.531	YES	0.453	YES	0.494	YES	1.012
12	YES	1.320	YES	1.168	YES	0.996	YES	1.086	NO	2.224
13	YES	1.102	YES	0.975	YES	0.831	YES	0.907	YES	1.857
14	NO	3.562	NO	3.150	NO	2.687	NO	2.931	NO	6.000
15	YES	0.606	YES	0.536	YES	0.457	YES	0.498	YES	1.020
16	YES	0.528	YES	0.467	YES	0.398	YES	0.434	YES	0.889
17	YES	0.829	YES	0.733	YES	0.625	YES	0.682	YES	1.396
18	YES	0.484	YES	0.428	YES	0.365	YES	0.398	YES	0.814
19	YES	0.334	YES	0.295	YES	0.252	YES	0.275	YES	0.563
20	YES	1.480	YES	1.309	YES	1.116	YES	1.217	NO	2.493
21	YES	0.634	YES	0.560	YES	0.478	YES	0.521	YES	1.067
22	NO	7.603	NO	6.724	NO	5.734	NO	6.255	NO	12.807
23	YES	1.500	YES	1.327	YES	1.131	YES	1.234	NO	2.527
24	YES	0.338	YES	0.299	YES	0.255	YES	0.278	YES	0.570
25	YES	0.469	YES	0.415	YES	0.354	YES	0.386	YES	0.790
26	YES	0.911	YES	0.806	YES	0.687	YES	0.750	YES	1.535
27	YES	0.755	YES	0.668	YES	0.570	YES	0.621	YES	1.272
28	YES	0.498	YES	0.440	YES	0.375	YES	0.409	YES	0.838
29	YES	0.440	YES	0.389	YES	0.332	YES	0.362	YES	0.741
30	YES	0.270	YES	0.239	YES	0.204	YES	0.222	YES	0.455
31	YES	0.218	YES	0.193	YES	0.165	YES	0.180	YES	0.368
32	YES	0.237	YES	0.210	YES	0.179	YES	0.195	YES	0.399
33	YES	0.451	YES	0.399	YES	0.340	YES	0.371	YES	0.760
34	YES	0.204	YES	0.181	YES	0.154	YES	0.168	YES	0.344
35	YES	0.257	YES	0.227	YES	0.194	YES	0.211	YES	0.432
36	YES	0.188	YES	0.167	YES	0.142	YES	0.155	YES	0.317
37	YES	0.146	YES	0.129	YES	0.110	YES	0.120	YES	0.246
38	YES	0.184	YES	0.162	YES	0.139	YES	0.151	YES	0.309
39	YES	0.147	YES	0.130	YES	0.111	YES	0.121	YES	0.248
40	YES	0.170	YES	0.150	YES	0.128	YES	0.140	YES	0.286
41	YES	0.137	YES	0.121	YES	0.103	YES	0.113	YES	0.231
42	YES	0.185	YES	0.164	YES	0.140	YES	0.152	YES	0.312
43	YES	0.222	YES	0.196	YES	0.167	YES	0.183	YES	0.374
44	YES	0.157	YES	0.139	YES	0.119	YES	0.130	YES	0.265
45	YES	0.181	YES	0.160	YES	0.136	YES	0.149	YES	0.304

APPENDIX III

AEROBIC ESTIMATE OF SLUDGE BED LIFE

An estimate of the life of a sludge bed assuming aerobic decomposition is the only source of destruction that can be made by utilizing the oxygen uptake rate per square meter of bed area. It is assumed that the kinetics of decomposition are zero order. The total amount of oxygen required for the decomposition is approximated by the COD of the sludge material. The bed life is then calculated by dividing the total amount of oxygen required per square meter of bed by the rate of oxygen uptake per square meter. These calculations were performed for the five selected bed locations of the river survey; the calculations and results are given in Table L. A bed life of 300 to 400 years is predicted under these conditions.

TABLE L

AEROBIC ESTIMATE OF SLUDGE BED LIFE FOR FIVE SELECTED BEDS IN THE LOWER FOX RIVER

Nomenclature

C = average solids content of sludge bed, g./m.^{3}

$\underline{H}_{in}$ = sludge depth, in.

$\underline{H}$ = sludge depth, m. = $2.54 \times 10^{-2}\ \underline{H}_{in}$

$\underline{k}_s$ = oxygen uptake rate, g. O_2/m.^{2}/day

COD = chemical oxygen demand, g. O_2/g. dry sludge

$\underline{T}_d$ = bed life, days

$\underline{T}$ = bed life, years = $\underline{T}_d/365$

Calculation

$\underline{T}_d = \underline{C} \times \underline{H} \times COD/\underline{k}_s$

$\underline{C}$ = 0.05 g. dry sludge/ml. = 5×10^4 g./m.^{3}

$\underline{H} = 2.54 \times 10^{-2}\ \underline{H}_{in}$

$\underline{k}_s$ = 0.153 g. O_2/m.^{2}/day [from (20)]

$\underline{T}_d = 5.0 \times 10^4 \times 2.54 \times 10^{-2}\ \underline{H}_{in} \times COD/0.153 = 8320 \times \underline{H}_{in} \times COD$

$\underline{T} = 22.8 \times \underline{H}_{in} \times COD$

Results for Five Selected Beds

B 1: $\underline{T} = 22.8 \times 30 \times 0.650 = 444$ years

B 6: $\underline{T} = 22.8 \times 36 \times 0.380 = 313$ years

B 14: $\underline{T} = 22.8 \times 60 \times 0.295 = 403$ years

B 22: $\underline{T} = 22.8 \times 60 \times 0.265 = 362$ years

B 24: $\underline{T} = 22.8 \times 60 \times 0.305 = 416$ years

APPENDIX IV

COMPOSITION OF MODEL SLUDGE SYSTEM

The model sludge system used in the experiments demonstrating the existence of anaerobic decomposition consisted of the following:

Distilled water	1000 ml.	
Bleached kraft pulp (Kimberly-Clark Corp. LL 18)	25 g.	
Long fiber acid-washed asbestos (Powmineo) (Matheson, Coleman, and Bell)	8.33 g.	as metal ion
$CaCl_2$	0.554 g.	200 mg./l.
$MgCl_2 \cdot 6H_2O$	0.836 g.	100 mg./l.
$FeCl_3 \cdot 6H_2O$	0.097 g.	20 mg./l.
KCl	0.0383 g.	20 mg./l.
$MnSO_4 \cdot H_2O$	0.079 g.	25 mg./l.
NaCl	0.504 g.	200 mg./l.
Buffer morpholinopropane sulfonic acid	20.7 g.	

APPENDIX V

MASS BALANCE ON RADIOACTIVITY IN ^{14}C-LABELLING EXPERIMENT

FOR THE ^{14}C-LABELLED KRAFT PULP ADDITION

Total gas produced = 294 ml.

Volume average count for gas produced as measured by sampling technique = 1500 counts/min. =

$$\frac{\sum \text{(individual counts)(ml. gas produced in that sampling period)}}{\sum \begin{array}{c}\text{gas produced in each}\\ \text{sampling period}\end{array} = \text{total gas produced}}$$

The system was sampled every 36 hr. Ten ml. of gas from the Warburg apparatus was absorbed in 5 ml. NCS, but only 2 ml. NCS solution was counted. The counts detected are quenched by the presence of the NCS and compensation for the quenching can be made by using Fig. 12, p. 39. All samples counted had an external standard ratio of about 4.4, so the quenched counts need to be multiplied by 3.25 to get the actual disintegrations per minute.

1500 counts/min. x 5/2 x 3.25 = 1.21×10^4 av. counts/min./10 ml.

Since the gas evolved is approximately half carbon dioxide and half methane and the ^{14}C-labelled methane is not detected by the counting technique used, the actual activity given off is twice that detected, assuming that the methane is labelled to the same extent as the carbon dioxide. Thus, the total average activity per 10 ml. of gas produced =

$1.21 \times 10^4 \times 2 = 2.42 \times 10^4$ counts/min./10 ml.

The total activity given off at the end of 22 days =

$$294 \text{ ml.} \times 2.42 \times 10^4 \text{ counts/min./10 ml.} = 6.6 \times 10^5 \text{ counts/min.}$$

Converting into millicuries of activity:

$$\frac{6.6 \times 10^5 \text{ counts/min./60 sec./min.}}{3.7 \times 10^4 \text{ counts/sec./mc.}} = 0.3 \text{ mc.}$$

The initial activity added in the aspen kraft pulp was

$$2.35 \text{ mc./g.} \times 0.18 \text{ g.} = 0.423 \text{ mc.}$$

So at the end of 22 days, 0.3/0.423 x 100 = 71% of the activity intially added had evolved as gas.

FOR THE ^{14}C-LABELLED SIMULATED GROUNDWOOD ADDITION

The same calculation procedure as above is followed.

Total gas produced = 244 ml.

Volume average count = 3200 counts/min.

Actual disintegrations per minute =

$$3200 \times 5/2 \times 3.25 = 2.6 \times 10^4 \text{ counts/min./10 ml.}$$

Total average activity = $2.6 \times 10^4 \times 2 = 5.20 \times 10^4$ counts/min./10 ml.

Total activity given off in 22 days =

$$244 \text{ ml.} \times 5.20 \times 10^4 \text{ counts/min./10 ml.} = 1.27 \times 10^6 \text{ counts/min.}$$

Converting to millicurie of activity:

$$1.27 \times 10^6/60/3.7 \times 10^4 = 0.574 \text{ mc.}$$

Initial activity added in the aspen simulated groundwood:

$$7.3 \text{ mc./g.} \times 0.18 \text{ g.} = 1.31 \text{ mc.}$$

So at the end of 22 days, 0.574/1.31 x 100 = 44% of the activity initially added had evolved as gas.

RATE COMPARISON

Since the same amount of kraft pulp and simulated groundwood pulp were added, the average ratio of the rates of decomposition is kraft pulp/simulated groundwood pulp = 71/44 = 1.6. Aspen kraft pulp decomposes faster than aspen simulated groundwood pulp by a factor of about two.

APPENDIX VI

MASS TRANSFER CONSIDERATIONS

If the problem of how mass is transported within the fibrous sludge is considered, several mechanisms suggest themselves. The mechanisms which seem reasonable are diffusion, dispersion due to flow, mixing due to free convection caused by the temperature gradient, and mixing due to gas evolution.

GAS EVOLUTION

The mixing due to gas evolution is unimportant due to the nature of the gas evolution. Gas produced within the bed does not readily escape and cause stirring. The gas remains trapped within the pore structure of the bed and is released only when a sufficient quantity is entrapped to cause the bed to crack. These cracks affect only a small amount of the total bed volume. Often a portion of the bed will be floated to the water surface, intact, by the trapped gases, and this is the source of the floating sludge problem.

PERMEABILITY STUDIES

In order to determine whether dispersion due to fluid flow within the bed is important, an estimate of bed permeability had to be made.

The apparatus used was basically the same as that used in the Engineering Department at the Institute. It consisted of the components shown in Fig. 36.

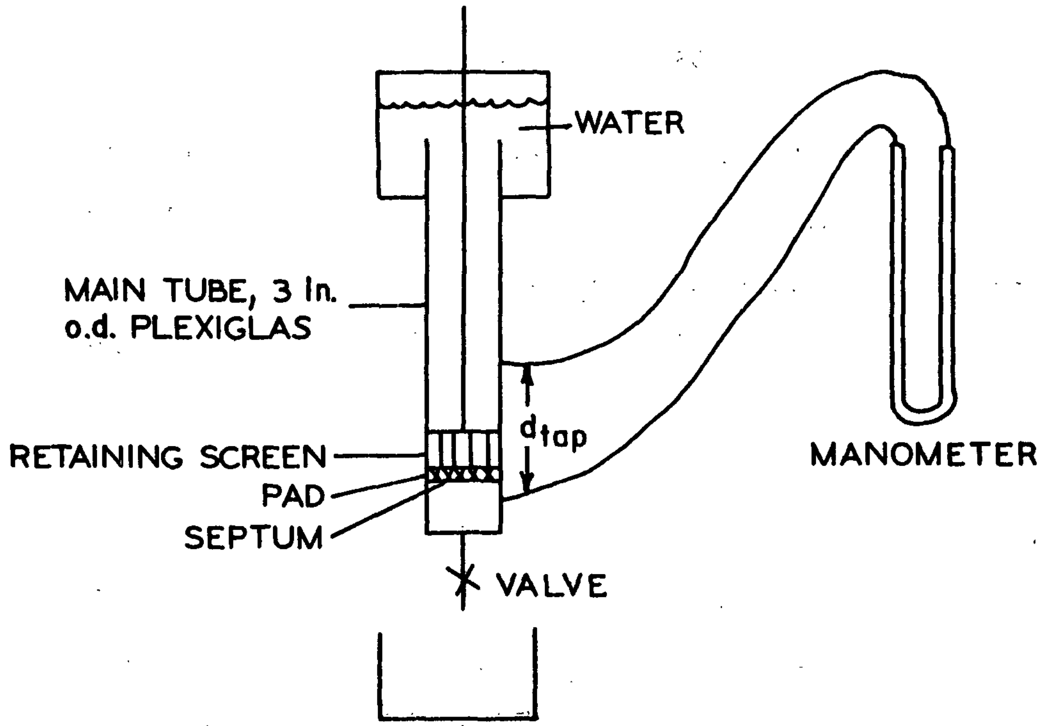

Figure 36. Apparatus for Determining Bed Permeability

The procedure consisted of filling the main tube 2/3 full of water, purging the manometer lines of air, weighing out either 100 or 150 g. of water-saturated sludge, placing the sludge in the main tube and stirring well to disperse, letting the sludge settle for from one to four hours, placing a retaining screen over the top of the sludge, opening the bottom valve full several times (at least 10) to condition the mat, adjusting the flow rate, recording the flow rate with graduate and stopwatch, recording the pressure drop registered by the manometer, and measuring the pad thickness. The last four steps were repeated several times for different flow rates. The permeability was calculated from the formula

$$K = \mu V/(dP/dZ)$$

in which μ is viscosity of water, $\underline{V}$ is superficial velocity, and $d\underline{P}/d\underline{Z}$ is pressure drop. $d\underline{P}/d\underline{Z}$ is approximated by $\Delta\underline{P}/\underline{t}$, pressure drop/pad thickness. $\Delta\underline{P}$ is given by

$$\Delta P = g[h_m(\rho_{TBE} - \rho_{H_2O}) + \rho_{H_2O}\, d_{tap}]$$

where $\underline{g}$ is the acceleration due to gravity, $\underline{h}_m$ is the manometer reading, ρ_{TBE} is the density of tetrabutyl ethane, 2.96 g./cm.^{3}, ρ_{H_2O} is the density of water, 1.0 g./cm.^{3}, and $\underline{d}_{tap}$ is the distance between taps.

SAMPLE CALCULATION

$\Delta\underline{P}$ = 980 [(2.54 x 9.89)(1.96) + 17.4] = 65,600 dynes

$\Delta\underline{Z}$ = $\underline{t}$ = 2.37 cm.

$d\underline{P}/d\underline{Z}$ = 27,600 dynes/cm.

$\underline{V}$ = 0.178 cm.^{3}/sec./17.9 cm.^{2} = 9.95×10^{-3} cm./sec.

μ = 0.01 poise

$\underline{K}$ = $10^{-2} \times 9.95 \times 10^{-3}/2.76 \times 10^4 = 3.60 \times 10^{-9}$

CALCULATION OF BED SUPERFICIAL VELOCITY AND REYNOLDS NUMBER

The superficial velocity of water flowing through the sludge bed is given by

$$V = \rho\, g\, K \cos(\beta)/\mu$$

where ρ is the density of water, 1.0 g./cm.^{3}; $\underline{g}$ is the acceleration due to gravity; $\underline{K}$ is the permeability, 3×10^{-9}; β is the angle between the slope of the river bottom and the vertical, 80° in this case assuming a 10° bottom slope; and μ is the viscosity of water, 0.01 poise. These values in the above equation give a superficial velocity of 5×10^{-5} cm./sec.

Based on this velocity a Reynolds number can be calculated if the particle diameter, D, is assumed to be approximately 0.001 cm. (the order of magnitude of a fiber diameter).

$$Re = \rho \, DV/\mu = 3 \times 10^{-6}$$

A study of Harleman and Rumer (71) indicates that at a Reynolds number of 10^{-3} diffusion is as important as dispersion. Therefore, at a Reynolds number of 10^{-6} dispersion should be negligible.

AN ESTIMATE OF THE MAGNITUDE OF FREE CONVECTION CURRENTS IN THE INTERSTICES OF A SLUDGE BED

The order of magnitude was calculated by considering a case where the velocities were greater than those expected in the pores of the sludge bed. The case was that of the velocity created by free convection between two parallel plates, each at a different temperature, separated by a distance 2b. The maximum velocity is given by (72)

$$v_{max} = \rho \, \xi \, gb^2 \, \Delta T/32 \, \mu$$

where b is 1/2 the plate separation, 5×10^{-5} cm., the approximate pore radius in sludge (this approximation is justified below); ΔT is the temperature difference, 5°C. per 50 cm. x $5 \times 10^{-5} = 5 \times 10^{-6}$°C.; g is the acceleration due to gravity, 980 cm./sec.^{2}; ρ is the density of water, 1.0 g./cm.^{3}; μ is the viscosity, 0.01 poise; and ξ is the volume expansivity, 8.53×10^{-5}°C.$^{-1}$ $[(1/V)(\Delta V/\Delta T)_P]$. A calculation using these values gives a maximum velocity of 3.28×10^{-12} cm./sec. This velocity is so low that mixing created by this velocity would be negligible in comparison to molecular diffusion.

CALCULATION OF MEAN PORE SIZE

The permeability of the sludge is 3×10^{-9}. Permeability can be expressed as

$$K = \varepsilon^3 / k \mu S_o{}^2$$

where ε is porosity, S_o is specific surface area per unit volume, and k is the Kozeny constant. For porosities greater than 0.7, the Kozeny constant is a function of porosity (see Table LI and Fig. 37). The sludge porosity is 0.93; corresponding Kozeny constants are 29 for flow past spheres, 17.5 for flow perpendicular to cylinders, and 12.5 for flow parallel to cylinders. Since the sludge system consists largely of randomly-oriented fibers (cylinders) with some spherical particles, 18 was chosen as a representative constant.

TABLE LI

VALUES OF THE KOZENY CONSTANT AS A FUNCTION OF POROSITY
[From Happel (73)]

Fractional Void Volume	Kozeny Constant for Flow: Parallel to Cylinders	Perpendicular to Cylinders	Past Assemblage of Spheres
0.99	31.10	53.83	71.63
0.90	7.31	11.03	11.34
0.80	5.23	7.46	7.22
0.70	4.42	6.19	5.69
0.60	3.96	5.62	5.11
0.50	3.67	5.38	4.74
0.40	3.44	5.28	4.54

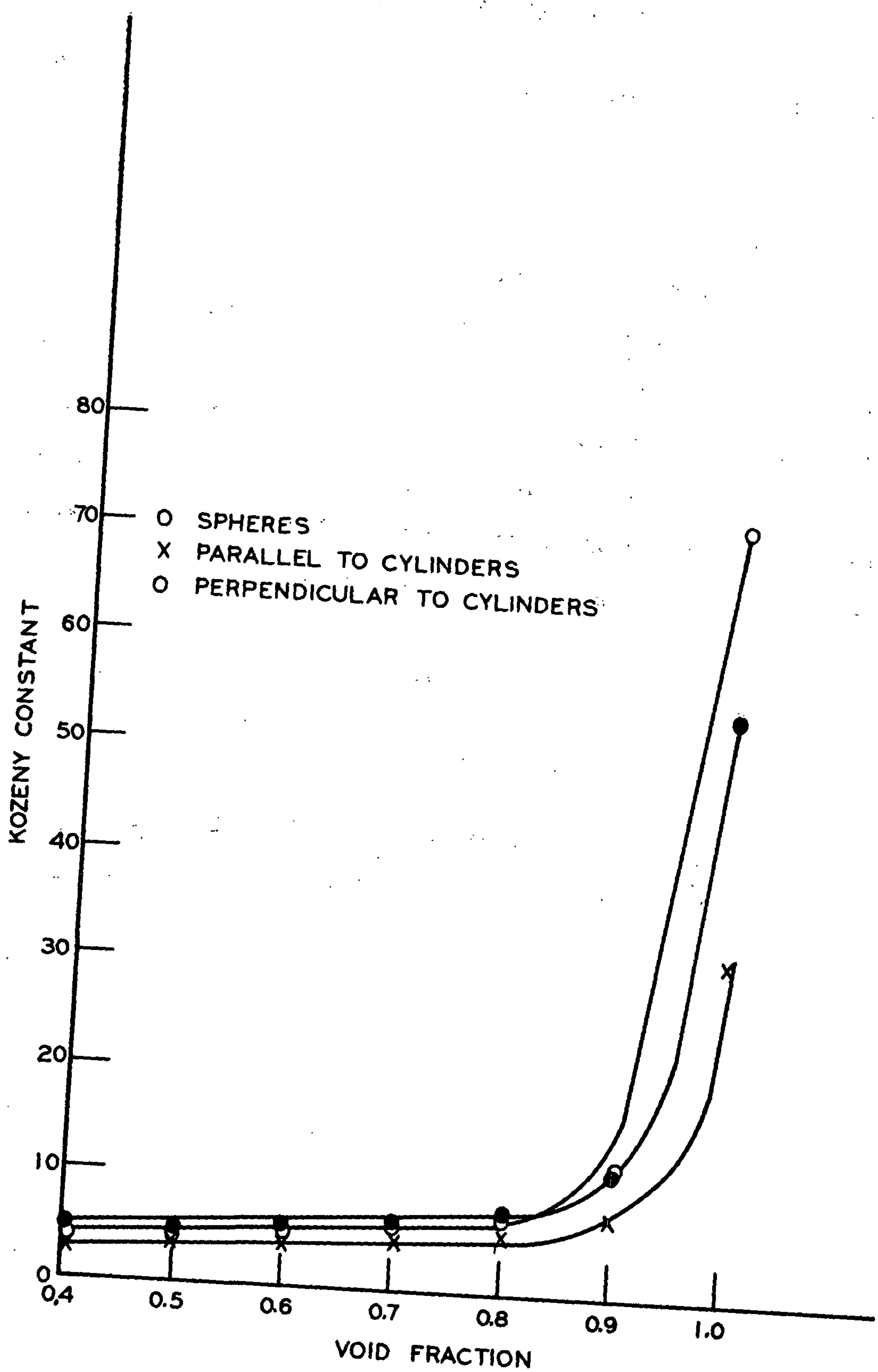

Figure 37. Kozeny Constant as a Function of Porosity [from Happel (73)]

Solving the formula given above for S_o gives 3.86×10^4 cm.^{2}/cm.^{3} If it is assumed that all the voids in the system are spherical,

$$S_o = \sum_{i=1}^{n} 4\pi r_i^{\,2} = 4\pi n\bar{r}_i^{\,2}$$

where $\bar{r}_i$ is the average pore radius.

$$V_o = \sum_{i=1}^{n} 4\pi r_i^{\,3}/3 = 4\pi n\bar{r}_i^{\,3}/3 = 0.93 \text{ cm.}^3$$

where V_o is the void volume per unit volume. Solving these two equations for average pore radius, $\bar{r}_i$, gives 7.21×10^{-5} cm. or, as an order of magnitude figure, 5×10^{-5} cm. for the representative pore size in the sludge.

CONCLUSION

Considering all of the likely mechanisms for mass transfer within a sludge bed, diffusion appears to be the dominant mechanism.

APPENDIX VII

DETERMINATION OF GAS COMPOSITION

A computer program was written which transforms the peak heights and half-height widths of the gas chromatography data into gas composition. The program then takes this data and calculates a flask constant for each Warburg flask which enables the calculation of volume of gas generated from the measured pressure (mm. of Hg). The flask constant compensates for solubility of the gases in the liquid through the application of Henry's law and also applies the simple ideal gas law to the system. The program also calculates the methane fraction that is evolved each day.

The program is given in Table LII. The nomenclature used in the program is as follows:

GMM = generated pressure (mm. of Hg)

QINJ = quantity of gas injected into gas chromatograph

PHN2 = peak height for nitrogen

PWN2 = peak width at half height for nitrogen

PAN2 = peak area for nitrogen

PHCO2, PWCO2, PACO2, PHCH4, PWCH4, and PACH4 are the same quantities for carbon dioxide and methane

VFL = volume of flask that is liquid

VFG = volume of flask that is gas

FCH4 = fraction of gas that is methane

FCO2 = fraction of gas that is carbon dioxide

FN2 = fraction of gas that is nitrogen

SGAS = sum of gas evolved to this point for this flask

EGAS	= evolved gas
FC	= flask constant
T	= temperature, ^{o}K
PATM	= atmospheric pressure
ACO2	= solubility of CO_2 at partial pressure of 1 atm. (ml. gas per ml. liquid)
AN2	= solubility of nitrogen at partial pressure of 1 atm. ACO2 and AN2 are the Henry's law constants
I	= vessel
J	= iteration number
QN2	= quantity of nitrogen for that injection
QCH4	= quantity of methane for that injection
QCO2	= quantity of carbon dioxide for that injection
RMECO	= ratio of methane to carbon dioxide
EFCH4	= evolved fraction that is methane

This program was applied to the laboratory results obtained using the Warburg apparatus; the resulting calculations are given in Tables LII through LVIII.

The quantity "evolved fraction that is methane" ($EFCH_4$) has a high degree of uncertainty because it is determined as the small difference between two large numbers. The individual quantities calculated probably have little meaning but their overall average would have significance.

TABLE LII

PROGRAM FOR GAS COMPOSITION CALCULATIONS

```
/JOB GO,TIME=30                                                          11/10/71
/FTC LIST
BPS FORTRAN D COMPILER                                                   11/10/71
           C      GAS COMPOSITION PROGRAM
 S.0001           DIMENSION GMM(20,50 ),QINJ(20,50 ),PHN2(20,50 ),PWN2(20,50 ),
                 1PHCO2(20,50 ),PWCO2(20,50 ),PHCH4(20,50 ),PWCH4(20,50 ),FCH4(50)
 S.0002           DIMENSION VFG(20),SGAS(50),EFCH4(20),FC(20,50),EGAS(20,50)
 S.0003           DIMENSION FCO2(50)
 S.0004            READ(5,1) ACO2,AN2,T,PATM,VFL,K,L,N
 S.0005         1 FORMAT(5F10.4,3I5)
 S.0006           WRITE(6,15)ACO2,AN2,T,PATM,VFL,K,L,N
 S.0007        15 FORMAT(1H ,5F10.4,3I5)
 S.0008            DO 9 I=1,L
 S.0009            READ(5,2)VFG(I)
 S.0010         2 FORMAT(F15.6)
 S.0011            WRITE(6,22)VFG(I)
 S.0012        22 FORMAT(1H ,F15.6)
 S.0013         9 CONTINUE
 S.0014           DO 10 J=1,N
 S.0015           DO 11 I=1,L
 S.0016           READ(5,3)GMM(I,J),QINJ(I,J),PHN2(I,J),PWN2(I,J),PHCH4(I,J),PWCH4(I
                 1,J),PHCO2(I,J),PWCO2(I,J)
 S.0017         3 FORMAT(8F8.4)
 S.0018           WRITE(6,33)GMM(I,J),QINJ(I,J),PHN2(I,J),PWN2(I,J),PHCH4(I,J),PWCH4
                 1(I,J),PHCO2(I,J),PWCO2(I,J)
 S.0019        33 FORMAT(1H ,8F8.4)
 S.0020        11 CONTINUE
 S.0021        10 CONTINUE
 S.0022           WRITE(6,31)
 S.0023        31 FORMAT(77H        I        J  QINJ    QN2     QCH4    QCO2    RMECO EGAS
                 1  SGAS     EFCH4   GMM)
 S.0024           DO 20 I=K,L
 S.0025           DO 21 J=1,N
 S.0026        12  PAN2      =PHN2(I,J)*PWN2(I,J)
 S.0027           PACO2      =PHCO2(I,J)*PWCO2(I,J)
 S.0028           PACH4      =PHCH4(I,J)*PWCH4(I,J)
 S.0029           QN2=PAN2*.108
 S.0030           QCH4=PACH4*.122
 S.0031           QCO2=PACO2*.0925
 S.0032           QT=QN2&QCH4&QCO2
 S.0033        16 RMECO=QCH4/QCO2
 S.0034           FCO2(J)=QCO2/QT
 S.0035           FN2=QN2/QT
 S.0036           FCH4(J)=QCH4/QT
 S.0037        17 FC(I,J)= (VFG(I)   *273.0/T&VFL*(ACO2*FCO2(J)  &AN2*FN2      ))/PATM
 S.0038            EGAS(I,J)=FC(I,J)*GMM(I,J)
 S.0039           SGAS(I)=SGAS(I)&EGAS(I,J)
 S.0040           M=J-1
 S.0041           IF(M)18,18,19
 S.0042        18 EFCH4(I)=QCH4/(QCH4&QCO2)
 S.0043           GO TO 100
 S.0044        19 EFCH4(I)   =((EGAS(I,J)&VFG(I))*FCH4(J)   -VFG(I)*FCH4(M)   )/EGAS(I,
                 1J)
 S.0045       100 WRITE(6,32)I,J,QINJ(I,J),QN2,QCH4,QCO2,RMECO,EGAS(I,J),SGAS(I),
                 1EFCH4(I),GMM(I,J)
 S.0046        32 FORMAT(1H ,2I7,6F7.3,F8.3,2F7.3)
 S.0047        21 CONTINUE
 S.0048        20 CONTINUE
 S.0049           STOP
 S.0050           END
```

TABLE LIII

GAS COMPOSITION DATA FOR
PROOF OF CELLULOSE DECOMPOSITION EXPERIMENT

I[a]	J	QINJ	QN2	QCH4	QCO2	RMECO	EGAS	SGAS	EFCH4	GMM	Average RMECO	Average EFCH4
1	1	1.000	0.823	0.015	0.099	0.151	16.987	16.987	0.132	17.400		
1	2	1.000	0.770	0.048	0.162	0.294	18.097	35.084	0.182	17.800		
1	3	1.000	0.480	0.297	0.284	1.046	20.380	55.464	1.120	18.800		
1	4	1.000	0.419	0.410	0.343	1.193	25.749	81.213	0.549	23.400		
1	5	1.000	0.328	0.439	0.382	1.150	21.975	103.188	0.491	19.500		
1	6	1.000	0.194	0.510	0.423	1.206	18.258	121.445	0.739	15.800		
1	7	1.000	0.272	0.502	0.407	1.233	15.433	136.878	0.292	13.600		
1	8	1.000	0.249	0.451	0.405	1.114	15.869	152.747	0.329	13.800		
1	9	1.000	0.245	0.483	0.412	1.172	19.029	171.776	0.484	16.600		
1	10	1.000	0.229	0.480	0.433	1.108	20.622	192.398	0.408	17.800		
1	11	1.000	0.105	0.568	0.491	1.156	20.772	213.170	0.729	17.500		
1	12	1.000	0.067	0.544	0.490	1.112	21.283	234.453	0.518	17.700		
1	13	1.000	0.086	0.560	0.531	1.055	15.812	250.265	0.387	13.100		
1	14	1.000	0.082	0.533	0.484	1.103	16.794	267.059	0.528	14.000		
1	15	1.000	0.244	0.470	0.460	1.022	14.126	281.185	-0.044	12.100		
1	16	1.000	0.073	0.592	0.550	1.075	12.685	293.870	0.989	10.500	1.0119	0.4896
2	1	1.000	0.840	0.020	0.111	0.176	17.697	17.697	0.150	17.800		
2	2	1.000	0.842	0.061	0.212	0.290	19.138	36.835	0.192	18.300		
2	3	1.000	0.599	0.320	0.299	1.070	17.511	54.346	1.150	16.200		
2	4	1.000	0.402	0.367	0.306	1.202	18.369	72.716	0.664	16.600		
2	5	1.000	0.378	0.438	0.355	1.234	14.883	87.599	0.537	13.300		
2	6	1.000	0.314	0.424	0.355	1.194	12.357	99.956	0.471	10.900		
2	7	1.000	0.242	0.487	0.396	1.232	13.818	113.773	0.679	12.000		
2	8	1.000	0.233	0.361	0.305	1.183	11.435	125.208	0.194	10.000		
2	9	1.000	0.169	0.533	0.424	1.256	15.887	141.095	0.811	13.600		
2	10	1.000	0.152	0.544	0.439	1.239	16.333	157.428	0.509	13.900		
2	11	1.000	0.134	0.568	0.481	1.181	16.403	173.830	0.484	13.800		
2	12	1.000	0.142	0.516	0.429	1.204	17.234	191.064	0.453	14.600		
2	13	1.000	0.117	0.560	0.512	1.095	13.377	204.441	0.450	11.100		
2	14	1.000	0.083	0.573	0.509	1.125	14.632	219.072	0.596	12.100		
2	15	1.000	0.088	0.571	0.499	1.145	13.253	232.326	0.501	11.000		
2	16	1.000	0.071	0.510	0.451	1.131	11.730	244.055	0.500	9.700	1.0598	0.5213
3	1	1.000	0.989	0.023	0.127	0.180	16.917	16.917	0.153	17.300		
3	2	1.000	0.727	0.059	0.180	0.325	19.239	36.156	0.216	18.700		
3	3	1.000	0.603	0.325	0.300	1.086	17.366	53.522	1.132	16.300		
3	4	1.000	0.467	0.404	0.327	1.234	17.679	71.200	0.639	16.300		
3	5	1.000	0.380	0.432	0.344	1.257	13.978	85.178	0.566	12.700		
3	6	1.000	0.314	0.400	0.332	1.206	11.809	96.987	0.435	10.600		
3	7	1.000	0.300	0.500	0.409	1.223	13.087	110.074	0.591	11.600		
3	8	1.000	0.273	0.466	0.377	1.234	11.167	121.240	0.441	9.900		
3	9	1.000	0.228	0.456	0.366	1.246	15.661	136.901	0.514	13.800		
3	10	1.000	0.175	0.549	0.425	1.291	14.939	151.840	0.692	13.000		
3	11	1.000	0.160	0.483	0.398	1.213	14.589	166.429	0.395	12.600		
3	12	1.000	0.128	0.415	0.351	1.183	15.955	182.384	0.464	13.700		
3	13	1.000	0.164	0.537	0.492	1.091	11.785	194.169	0.362	10.000		
3	14	1.000	0.107	0.400	0.352	1.136	13.060	207.229	0.554	11.100		
3	15	1.000	0.128	0.566	0.490	1.156	11.790	219.019	0.558	10.000		
3	16	1.000	0.140	0.537	0.465	1.156	9.984	229.003	0.412	8.500	1.0761	0.5078
	C0000											

[a] $\underline{I}$ = 1 for kraft pulp sample, 2 for simulated groundwood sample, and 3 for control.

TABLE LIV

GAS COMPOSITION DATA FOR STIMULATED DECOMPOSITION EXPERIMENTS

	I	J	QINJ	QN2	QCH4	QCO2	RMECO	EGAS	SGAS	EFCH4	GMM
H-P	1	1	2.000	19.077	0.092	0.100	0.921	18.358	18.358	0.480	20.420
	1	2	2.000	1.909	0.206	0.129	1.592	3.922	22.280	1.717	4.200
	1	3	2.000	1.742	0.307	0.168	1.826	3.991	26.271	0.997	4.220
	1	4	2.000	1.649	0.386	0.144	2.678	4.318	30.589	0.834	4.600
	1	5	2.000	1.750	0.360	0.168	2.139	3.333	33.922	-0.265	3.530
	1	6	2.000	1.597	0.395	0.181	2.180	2.566	36.488	0.861	2.700
	1	7	1.000	0.731	0.236	0.099	2.384	3.041	39.529	1.176	3.180
	1	8	1.000	0.677	0.257	0.115	2.237	4.150	43.679	0.662	4.290
	1	9	1.000	0.567	0.256	0.106	2.408	4.076	47.755	0.823	4.200
	1	10	2.000	1.158	0.594	0.255	2.328	6.333	54.088	0.532	6.470
	1	11	1.000	0.587	0.390	0.166	2.345	5.886	59.974	0.902	5.940
	1	12	1.000	0.391	0.325	0.113	2.875	7.183	67.157	0.916	7.300
	1	13	1.000	0.391	0.325	0.113	2.875	5.904	73.061	0.393	6.000
	1	14	2.000	0.899	0.893	0.377	2.365	8.278	81.339	0.580	8.200
	1	15	2.000	0.715	0.929	0.395	2.351	7.821	89.160	0.866	7.650
	1	16	2.000	0.629	0.979	0.434	2.256	8.280	97.440	0.692	8.000
	1	17	2.000	0.397	0.730	0.311	2.343	7.884	105.324	0.765	7.600
	1	18	2.000	0.429	0.805	0.383	2.103	6.414	111.737	0.393	6.100
	1	19	2.000	0.511	1.107	0.541	2.045	6.576	118.314	0.674	6.200
	1	20	2.000	0.517	1.234	0.592	2.086	6.689	125.003	0.683	6.300
	1	21	2.000	0.415	1.047	0.518	2.021	6.836	131.838	0.550	6.400
	1	22	2.000	0.408	1.059	0.548	1.934	6.880	138.719	0.493	6.400
H-N	2	1	2.000	1.868	0.110	0.100	1.099	20.064	20.064	0.524	21.710
	2	2	2.000	1.654	0.224	0.144	1.556	4.509	24.573	1.051	4.800
	2	3	2.000	1.638	0.333	0.194	1.713	4.757	29.330	0.808	5.000
	2	4	2.000	1.594	0.425	0.194	2.186	5.128	34.458	0.734	5.400
	2	5	2.000	1.502	0.483	0.207	2.332	3.911	38.369	0.751	4.100
	2	6	2.000	1.371	0.507	0.203	2.502	2.484	40.853	0.926	2.600
	2	7	1.000	0.661	0.274	0.110	2.498	3.266	44.119	0.687	3.400
	2	8	1.000	0.610	0.303	0.120	2.528	4.151	48.270	0.837	4.290
	2	9	1.000	0.622	0.325	0.129	2.513	4.076	52.346	0.458	4.200
	2	10	2.000	1.071	0.696	0.285	2.444	6.328	58.674	0.766	6.440
	2	11	1.000	0.546	0.415	0.178	2.336	6.005	64.679	0.670	6.040
	2	12	1.000	0.396	0.360	0.137	2.618	7.441	72.120	0.780	7.500
	2	13	1.000	0.439	0.467	0.181	2.583	6.202	78.322	0.742	6.200
	2	14	2.000	0.723	0.944	0.363	2.604	8.873	87.195	0.758	8.800
	2	15	2.000	0.657	1.034	0.401	2.582	8.744	95.939	0.739	8.600
	2	16	2.000	0.553	0.998	0.421	2.367	9.596	105.535	0.593	9.300
	2	17	2.000	0.316	0.773	0.317	2.435	10.187	115.722	0.862	9.800
	2	18	2.000	0.346	0.870	0.421	2.066	8.703	124.425	0.380	8.200
	2	19	2.000	0.380	1.097	0.563	1.949	9.774	134.199	0.584	9.100
	2	20	2.000	0.393	1.248	0.635	1.966	9.577	143.775	0.629	8.900
	2	21	2.000	0.295	1.094	0.582	1.880	9.675	153.451	0.606	8.900
	2	22	2.000	0.258	1.089	0.613	1.778	9.891	163.342	0.561	9.000
H-N	3	1	2.000	1.949	0.101	0.065	1.560	17.267	17.267	0.609	18.440
	3	2	2.000	1.757	0.190	0.092	2.078	4.085	21.352	0.929	4.320
	3	3	2.000	1.690	0.293	0.142	2.055	3.937	25.289	0.983	4.100
	3	4	2.000	1.642	0.410	0.166	2.462	3.609	28.898	1.161	3.740
	3	5	2.000	1.487	0.381	0.168	2.261	2.998	31.896	0.240	3.090
	3	6	2.000	1.388	0.425	0.183	2.318	2.148	34.044	1.112	2.200
	3	7	1.000	0.673	0.231	0.090	2.575	2.993	37.037	0.724	3.070
	3	8	1.000	0.673	0.258	0.104	2.491	4.004	41.041	0.569	4.080
	3	9	1.000	0.634	0.268	0.101	2.657	3.828	44.869	0.621	3.900
	3	10	2.000	1.166	0.637	0.228	2.787	5.974	50.843	0.889	6.040
	3	11	1.000	0.496	0.369	0.127	2.901	5.495	56.338	1.171	5.500
	3	12	1.000	0.467	0.293	0.125	2.350	7.463	63.800	-0.074	7.400
	3	13	1.000	0.429	0.424	0.153	2.775	6.190	69.990	1.514	6.100
	3	14	2.000	0.807	0.893	0.345	2.591	8.720	78.710	0.564	8.500
	3	15	2.000	0.735	0.943	0.383	2.462	8.196	86.906	0.648	7.900
	3	16	2.000	0.583	0.895	0.390	2.292	8.530	95.436	0.668	8.100
	3	17	2.000	0.421	0.730	0.335	2.178	9.578	105.013	0.584	9.000
	3	18	2.000	0.383	0.750	0.385	1.947	8.993	114.006	0.517	8.300
	3	19	2.000	0.452	1.059	0.607	1.745	11.281	125.287	0.542	10.200
	3	20	2.000	0.447	1.184	0.666	1.777	10.084	135.371	0.629	9.100
	3	21	2.000	0.324	0.953	0.566	1.683	8.960	144.331	0.531	8.000
	3	22	2.000	0.311	1.025	0.613	1.673	8.886	153.216	0.601	7.900

TABLE LIV. (Continued)

GAS COMPOSITION DATA FOR
STIMULATED DECOMPOSITION EXPERIMENTS

H-P	4	1	2.000	1.909	0.115	0.100	1.148	19.509	19.509	0.534	20.800
	4	2	2.000	1.706	0.228	0.122	1.868	5.712	25.221	0.850	6.040
	4	3	2.000	1.490	0.366	0.161	2.019	6.678	31.899	0.941	6.920
	4	4	2.000	1.325	0.439	0.211	2.083	7.482	39.380	0.646	7.660
	4	5	2.000	0.919	0.559	0.272	2.056	7.939	47.319	1.225	7.870
	4	6	2.000	1.069	0.556	0.301	1.850	6.758	54.077	-0.083	6.700
	4	7	2.000	0.994	0.670	0.285	2.352	8.919	62.995	0.824	8.900
	4	8	2.000	0.832	0.685	0.379	1.811	10.842	73.838	0.484	10.440
	4	9	2.000	0.698	0.772	0.421	1.832	10.328	84.165	0.743	9.800
	4	10	2.000	0.630	0.922	0.506	1.821	15.504	99.669	0.638	14.500
	4	11	2.000	0.559	0.976	0.569	1.714	15.269	114.958	0.539	14.080
	4	12	2.000	0.405	0.988	0.557	1.775	17.748	132.706	0.687	16.200
	4	13	2.000	0.341	1.069	0.614	1.739	14.952	147.658	0.632	13.500
	4	14	2.000	0.311	1.069	0.668	1.600	19.880	167.539	0.500	17.700
	4	15	2.000	0.227	1.058	0.671	1.577	16.450	183.989	0.627	14.500
	4	16	2.000	0.224	1.091	0.738	1.478	14.555	198.544	0.482	12.700
	4	17	2.000	0.143	0.837	0.598	1.401	14.722	213.266	0.526	12.700
	4	18	2.000	0.147	0.854	0.647	1.319	13.209	226.475	0.448	11.300
	4	19	2.000	0.123	1.150	0.883	1.302	14.281	240.756	0.613	12.100
	4	20	2.000	0.124	1.253	0.898	1.395	12.986	253.743	0.650	11.100
	4	21	2.000	0.220	1.032	0.792	1.304	10.722	264.464	0.188	9.200
	4	22	2.000	0.104	1.083	0.836	1.296	11.118	275.582	0.739	9.400
	5	1	2.000	1.901	0.146	0.111	1.319	20.979	20.979	0.569	21.990
H-P	5	2	2.000	1.515	0.285	0.149	1.908	6.093	27.072	1.111	6.280
	5	3	2.000	1.520	0.410	0.194	2.110	6.349	33.421	0.749	6.480
	5	4	2.000	1.390	0.523	0.233	2.245	6.282	39.703	0.853	6.340
	5	5	2.000	1.270	0.510	0.253	2.019	7.682	47.385	0.320	7.670
	5	6	2.000	1.152	0.534	0.302	1.935	7.020	54.406	0.669	6.900
	5	7	2.000	0.855	0.598	0.322	1.857	9.512	63.918	0.734	9.150
	5	8	2.000	0.863	0.672	0.403	1.670	11.548	75.466	0.413	10.920
	5	9	2.000	0.743	0.765	0.440	1.738	10.909	86.375	0.709	10.200
	5	10	2.000	0.608	0.852	0.496	1.719	16.534	102.908	0.630	15.200
	5	11	2.000	0.489	0.950	0.552	1.722	15.536	118.445	0.679	14.080
	5	12	2.000	0.425	0.996	0.586	1.699	19.374	137.818	0.569	17.400
	5	13	2.000	0.339	1.003	0.609	1.646	15.103	152.921	0.604	13.400
	5	14	2.000	0.294	1.112	0.693	1.605	19.706	172.627	0.590	17.300
	5	15	2.000	0.237	1.091	0.734	1.487	15.502	188.129	0.526	13.400
	5	16	2.000	0.207	1.101	0.760	1.449	14.557	202.686	0.549	12.500
	5	17	2.000	0.114	0.758	0.551	1.374	15.200	217.886	0.532	12.900
	5	18	2.000	0.127	0.869	0.641	1.356	13.111	230.997	0.522	11.100
	5	19	2.000	0.146	1.109	0.829	1.338	14.463	245.459	0.540	12.200
	5	20	2.000	0.217	1.135	0.866	1.310	11.453	256.912	0.377	9.700
	5	21	2.000	0.103	0.950	0.766	1.239	9.975	266.887	0.602	8.300
	5	22	2.000	0.097	1.054	0.842	1.252	10.701	277.588	0.575	8.900
Control	6	1/3+1	2.000	1.976	0.117	0.093	1.194	16.347	16.347	0.544	17.280
	6	2	2.000	1.679	0.207	0.126	1.652	5.553	21.900	0.773	5.800
	6	3	2.000	1.584	0.337	0.181	1.857	5.751	27.651	0.904	5.910
	6	4	2.000	1.555	0.424	0.194	2.181	5.322	32.973	0.683	5.460
	6	5	2.000	1.359	0.439	0.207	2.120	4.713	37.687	0.602	4.790
	6	6	2.000	1.192	0.492	0.232	2.120	4.182	41.868	0.932	4.200
	6	7	2.000	1.149	0.564	0.252	2.234	6.122	47.990	0.655	6.120
	6	8	2.000	1.034	0.561	0.271	2.072	7.830	55.820	0.434	7.740
	6	9	2.000	1.002	0.695	0.338	2.056	7.794	63.614	0.734	7.600
	6	10	2.000	0.870	0.864	0.401	2.152	11.280	74.894	0.823	10.850
	6	11	2.000	0.708	0.855	0.427	2.002	11.719	86.613	0.591	11.080
	6	12	2.000	0.607	0.960	0.466	2.059	14.086	100.698	0.698	13.200
	6	13	2.000	0.551	1.152	0.563	2.047	10.473	111.171	0.766	9.700
	6	14	2.000	0.442	1.003	0.531	1.889	11.702	122.873	0.503	10.700
	6	15	2.000	0.422	0.972	0.544	1.787	9.587	132.460	0.454	8.700
	6	16	2.000	0.338	1.039	0.640	1.625	10.704	143.164	0.611	9.500
	6	17	2.000	0.233	0.774	0.508	1.526	9.796	152.960	0.481	8.600
	6	18	2.000	0.213	0.817	0.516	1.584	9.559	162.519	0.663	8.400
	6	19	2.000	0.237	1.104	0.740	1.492	11.299	173.818	0.546	9.800
	6	20	2.000	0.269	1.098	0.659	1.665	9.509	183.327	0.630	8.400
	6	21	2.000	0.195	0.991	0.689	1.438	9.172	192.500	0.418	7.900
	6	2/3+22	2.000	0.198	1.049	0.762	1.377	10.290	202.790	0.478	8.800

TABLE LIV (Continued)

GAS COMPOSITION DATA FOR
STIMULATED DECOMPOSITION EXPERIMENTS

Control	7	1	2.000	1.976	0.109	0.084	1.287	15.563	15.563	0.563	16.500
	7	2	2.000	1.655	0.319	0.113	2.828	5.314	20.877	1.606	5.580
	7	3	2.000	1.580	0.322	0.144	2.232	5.608	26.485	0.216	5.820
	7	4	2.000	1.609	0.444	0.208	2.134	5.163	31.648	0.763	5.280
	7	5	2.000	1.315	0.401	0.201	1.992	4.488	36.136	0.421	4.550
	7	6	2.000	1.339	0.547	0.239	2.287	3.865	40.001	1.192	3.900
	7	7	1.000	0.601	0.287	0.127	2.254	4.697	44.698	0.686	4.700
	7	8	2.000	0.972	0.561	0.277	2.022	7.474	52.172	0.585	7.340
	7	9	2.000	1.020	0.705	0.350	2.017	7.301	59.474	0.649	7.100
	7	10	2.000	0.815	0.745	0.371	2.007	11.818	71.291	0.675	11.320
	7	11	2.000	0.639	0.786	0.408	1.923	11.432	82.723	0.710	10.740
	7	12	2.000	0.648	0.915	0.460	1.990	14.513	97.236	0.574	13.600
	7	13	2.000	0.547	0.966	0.506	1.909	11.435	108.671	0.650	10.560
	7	14	2.000	0.469	0.973	0.533	1.824	16.330	125.001	0.558	14.900
	7	15	2.000	0.360	1.022	0.560	1.826	13.961	138.962	0.707	12.600
	7	16	2.000	0.325	1.072	0.654	1.639	12.871	151.833	0.502	11.400
	7	17	2.000	0.227	0.848	0.530	1.599	12.846	164.679	0.559	11.300
	7	18	2.000	0.210	0.842	0.602	1.398	11.139	175.818	0.381	9.600
	7	19	2.000	0.217	1.061	0.770	1.379	14.018	189.836	0.568	12.000
	7	20	2.000	0.200	1.076	0.759	1.417	12.710	202.546	0.590	10.900
	7	21	2.000	0.172	0.939	0.679	1.382	11.237	213.783	0.496	9.600
	7	22	2.000	0.130	1.069	0.799	1.337	16.111	229.894	0.585	13.600
Salts	8	1	2.000	2.009	0.137	0.088	1.552	20.266	20.266	0.608	21.900
	8	2	2.000	1.771	0.249	0.128	1.950	6.137	26.403	0.771	6.540
	8	3	2.000	1.543	0.381	0.181	2.100	6.595	32.998	0.905	6.900
	8	4	2.000	1.523	0.512	0.227	2.261	7.410	40.408	0.680	7.680
	8	5	2.000	1.226	0.512	0.216	2.367	7.977	48.386	0.589	8.210
	8	6	2.000	1.115	0.604	0.275	2.194	7.523	55.908	0.702	7.600
	8	7	2.000	0.969	0.672	0.347	1.936	10.246	66.155	0.591	10.100
	8	8	2.000	0.829	0.752	0.370	2.030	12.229	78.384	0.669	11.940
	8	9	2.000	0.643	0.820	0.409	2.004	10.902	89.286	0.794	10.450
	8	10	2.000	0.581	0.966	0.466	2.073	16.406	105.692	0.668	15.600
	8	11	2.000	0.432	0.981	0.499	1.964	15.302	120.993	0.672	14.280
	8	12	2.000	0.418	1.072	0.553	1.939	15.036	136.030	0.582	13.950
	8	13	2.000	0.364	1.025	0.566	1.810	10.036	146.066	0.522	9.200
	8	14	2.000	0.288	1.032	0.608	1.698	12.856	158.922	0.598	11.600
	8	15	2.000	0.266	1.058	0.659	1.605	12.209	171.131	0.522	10.900
	8	16	2.000	0.218	1.026	0.666	1.541	13.462	184.593	0.558	11.900
	8	17	2.000	0.156	0.878	0.568	1.547	13.734	198.327	0.608	12.100
	8	18	2.000	0.146	0.846	0.615	1.376	11.316	209.644	0.384	9.800
	8	19	2.000	0.164	1.094	0.831	1.316	11.652	221.296	0.505	10.000
	8	20	2.000	0.187	1.165	0.923	1.262	10.185	231.481	0.430	8.700
	8	21	2.000	0.126	0.929	0.719	1.293	9.127	240.607	0.616	7.800
	8	22	2.000	0.110	1.061	0.807	1.316	14.413	255.020	0.602	12.300

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TABLE LV

GAS COMPOSITION DATA FOR TEMPERATURE STUDY (10°)

	I	J	QINJ	QN2	QCH4	QCO2	RMECO	EGAS	SGAS	EFCH4	GMM	Average RMECO	Average EFCH4
Agitated	1	1	1.000	0.922	0.029	0.065	0.445	4.478	4.478	0.308	4.800		
	1	2	1.000	0.815	0.073	0.088	0.830	6.842	11.320	0.568	7.200		
	1	3	1.000	0.817	0.083	0.114	0.728	3.090	14.409	0.249	3.200		
	1	4	1.000	0.759	0.113	0.097	1.161	3.923	18.332	0.755	4.100		
	1	5	1.000	0.812	0.168	0.169	0.995	5.239	23.571	0.564	5.300		
	1	6	1.000	0.692	0.159	0.161	0.989	2.192	25.763	0.509	2.200	1.0247	0.492
Stagnant	2	1	1.000	0.943	0.0	0.051	0.0	5.992	5.992	0.0	6.300		
	2	2	1.000	0.845	0.034	0.106	0.323	10.387	16.379	0.285	10.500		
	2	3	1.000	0.837	0.068	0.137	0.497	4.525	20.904	0.576	4.500		
	2	4	1.000	0.816	0.110	0.161	0.684	4.572	25.476	0.683	4.500		
	2	5	1.000	0.695	0.150	0.189	0.797	5.404	30.880	0.759	5.200		
	2	6	1.000	0.643	0.165	0.190	0.868	2.507	33.386	0.759	2.400	0.6338	0.612

TABLE LVI

GAS COMPOSITION DATA FOR TEMPERATURE STUDY (15°)

	I	J	QINJ	QN2	QCH4	QCO2	RMECO	EGAS	SGAS	EFCH4	GMM	Average RMECO	Average EFCH4
Agitated	1	1	1.000	0.901	0.010	0.078	0.126	4.012	4.012	0.112	4.200		
	1	2	1.000	0.829	0.059	0.083	0.703	6.813	10.825	0.606	7.100		
	1	3	1.000	0.780	0.135	0.122	1.103	8.041	18.867	0.768	8.200		
	1	4	1.000	0.687	0.185	0.153	1.211	7.311	26.177	0.691	7.300		
	1	5	1.000	0.532	0.200	0.146	1.358	8.608	34.785	0.631	8.500		
	1	6	1.000	0.595	0.257	0.181	1.418	5.704	40.490	0.521	5.600		
	1	7	1.000	0.474	0.322	0.202	1.594	12.641	53.131	0.754	12.200		
	1	8	1.000	0.435	0.342	0.244	1.402	5.412	58.542	0.505	5.100	1.275	0.5735
Stagnant	2	1	1.000	0.795	0.013	0.045	0.296	4.379	4.379	0.228	4.700		
	2	2	1.000	0.795	0.013	0.045	0.296	10.994	15.373	0.016	11.800		
	2	3	1.000	0.815	0.098	0.100	0.977	10.293	25.666	0.670	10.700		
	2	4	1.000	0.735	0.185	0.137	1.348	9.135	34.801	0.806	9.300		
	2	5	1.000	0.597	0.236	0.155	1.520	10.902	45.703	0.667	10.900		
	2	6	1.000	0.567	0.263	0.177	1.486	7.392	53.096	0.482	7.300		
	2	7	1.000	0.470	0.378	0.197	1.923	15.809	68.904	0.829	15.500		
	2	8	1.000	0.424	0.382	0.212	1.797	6.719	75.623	0.514	6.500	1.378	0.5265
STOP		00000											

TABLE LVII

GAS COMPOSITION DATA FOR TEMPERATURE STUDY (20°)

	I	J	QINJ	QN2	QCH4	QCO2	RMECC	EGAS	SGAS	EFCH4	GMM	Average RMECO	Average EFCH4
Agitated	1	1	1.000	0.804	0.049	0.150	0.326	13.308	13.308	0.246	13.200		
	1	2	1.000	0.703	0.070	0.163	0.427	7.176	20.484	0.342	7.000		
	1	3	1.000	0.636	0.198	0.224	0.883	18.044	38.528	0.648	17.200		
	1	4	1.000	0.408	0.195	0.178	1.096	16.313	54.841	0.535	15.400		
	1	5	1.000	0.356	0.297	0.244	1.217	15.784	70.625	0.713	14.500		
	1	6	1.000	0.336	0.354	0.277	1.274	25.810	96.435	0.464	23.500		
	1	7	1.000	0.227	0.390	0.299	1.305	13.383	109.818	0.762	11.900	0.9326	0.530
Stagnant	2	1	1.000	0.863	0.012	0.125	0.098	17.027	17.027	0.089	17.000		
	2	2	1.000	0.796	0.073	0.177	0.412	8.250	25.276	0.592	8.000		
	2	3	1.000	0.645	0.130	0.231	0.564	20.360	45.636	0.348	19.000		
	2	4	1.000	0.392	0.195	0.202	0.966	18.068	63.704	0.737	16.600		
	2	5	1.000	0.375	0.348	0.289	1.206	17.495	81.199	0.759	15.800		
	2	6	1.000	0.246	0.404	0.294	1.374	28.775	109.974	0.646	25.600		
	2	7	1.000	0.207	0.328	0.238	1.376	14.134	124.107	0.403	12.600	0.8566	0.510
STOP		CC000											

TABLE LVIII

GAS COMPOSITION DATA FOR SAMPLE VARIATION STUDY

I[a]	J	QINJ	QN2	QCH4	QCO2	RMECO	EGAS	SGAS	EFCH4	GMM	Average RMECO	Average EFCH4
1	1	1.000	0.883	0.010	0.051	0.192	5.457	5.457	0.161	5.800		
1	2	1.000	0.946	0.073	0.109	0.671	7.659	13.116	0.591	7.900		
1	3	1.000	0.636	0.146	0.166	0.877	17.276	30.391	0.535	16.900		
1	4	1.000	0.570	0.236	0.238	0.993	13.322	43.713	0.628	12.600		
1	5	1.000	0.423	0.287	0.229	1.250	13.663	57.376	0.732	12.800		
1	6	2.000	0.636	0.663	0.505	1.312	12.112	69.489	0.747	11.100		
1	7	2.000	0.618	0.717	0.559	1.282	13.769	83.257	0.439	12.500		
1	8	2.000	0.531	0.813	0.649	1.251	10.211	93.468	0.618	9.100		
1	9	1.000	0.501	0.828	0.662	1.250	11.379	104.847	0.468	10.100		
1	10	2.000	0.492	0.813	0.657	1.238	11.620	116.468	0.406	10.300		
1	11	2.000	0.353	0.861	0.705	1.221	10.121	126.588	0.699	8.800		
1	12	2.000	0.353	0.861	0.705	1.221	10.466	137.054	0.449	9.100	1.0632	0.5436
2	1	1.000	0.823	0.010	0.017	0.561	1.470	1.470	0.359	1.700		
2	2	1.000	0.895	0.007	0.023	0.317	0.955	2.425	-0.252	1.100		
2	3	1.000	0.980	0.024	0.048	0.505	0.970	3.395	1.117	1.100		
2	4	1.000	0.980	0.024	0.048	0.505	0.529	3.924	0.023	0.600		
2	5	1.000	0.996	0.022	0.042	0.522	0.527	4.451	-0.306	0.600		
2	6	1.000	0.996	0.022	0.042	0.522	0.263	4.715	0.021	0.300		
2	7	1.000	0.796	0.037	0.037	0.989	0.176	4.890	8.487	0.200		
2	8	1.000	0.796	0.037	0.037	0.989	0.264	5.154	0.042	0.300		
2	9	1.000	0.919	0.043	0.055	0.759	0.444	5.598	0.025	0.500		
2	10	1.000	0.919	0.043	0.055	0.759	0.621	6.220	0.042	0.700		
2	11	1.000	0.919	0.043	0.055	0.759	0.178	6.397	0.042	0.200		
2	12	1.000	0.975	0.047	0.050	0.940	0.794	7.191	0.207	0.900	0.6798	0.8167
3	1	1.000	0.801	0.013	0.091	0.140	13.357	13.357	0.123	13.700		
3	2	1.000	0.831	0.041	0.157	0.251	12.529	25.886	0.192	12.400		
3	3	1.000	0.661	0.134	0.248	0.541	23.387	49.273	0.410	21.900		
3	4	1.000	0.389	0.330	0.279	1.185	13.592	67.864	1.137	17.000		
3	5	1.000	0.328	0.421	0.316	1.332	19.665	87.529	0.638	17.800		
3	6	2.000	0.492	0.834	0.649	1.285	19.708	107.237	0.523	17.500		
3	7	2.000	0.390	0.915	0.718	1.275	22.305	129.542	0.552	19.500		
3	8	2.000	0.312	0.921	0.731	1.251	17.331	146.873	0.541	15.000		
3	9	1.000	0.253	0.979	0.765	1.280	20.579	167.452	0.567	17.700		
3	10	2.000	0.243	0.774	0.638	1.213	21.081	188.533	0.388	18.100		
3	11	2.000	0.142	0.844	0.699	1.207	19.069	207.602	0.629	16.100		
3	12	1.000	0.200	0.799	0.693	1.154	20.076	227.678	0.367	17.000	1.0112	0.5056
4	1	1.000	1.054	0.012	0.039	0.314	4.418	4.418	0.239	4.700		
4	2	1.000	1.054	0.012	0.039	0.314	3.572	7.990	0.011	3.800		
4	3	1.000	0.962	0.056	0.089	0.632	5.919	13.909	0.552	6.100		
4	4	1.000	0.808	0.143	0.105	1.351	4.324	18.233	1.609	4.400		
4	5	1.000	0.695	0.159	0.109	1.453	4.066	22.298	0.698	4.100		
4	6	1.000	0.644	0.187	0.133	1.401	3.831	26.130	0.759	3.800		
4	7	1.000	0.642	0.195	0.133	1.455	4.030	30.160	0.341	4.000		
4	8	1.000	0.581	0.226	0.150	1.506	2.959	33.119	1.120	2.900		
4	9	1.000	0.594	0.299	0.191	1.564	3.410	36.529	1.143	3.300		
4	10	1.000	0.540	0.287	0.189	1.515	3.952	40.481	0.408	3.800		
4	11	1.000	0.609	0.268	0.169	1.586	3.173	43.654	-0.353	3.100		
4	12	1.000	0.618	0.302	0.172	1.755	2.245	45.899	0.949	2.200	1.2388	0.623

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[a] I = 1 for B 1 samples, 2 for B 22, 3 for SXIII, and 4 for SX.